agso RESEARCH NEWSLETTER

'Geoscience for Australia's Future'

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Prospective hot-dry-rock geothermal energy in Australia

A vast resource underfoot

A hot-dry-rock (HDR) resource that could be used for generating electricity resides within the top 5 km of the Australian continental crust. This resource could supply all of Australia's energy requirements at current usage for the next 7500 years. Over 80 per cent of this resource lies beneath the Eromanga Basin, in western Queensland and northeastern South Australia.

These remarkable conclusions have issued from an AGSO study, now almost completed, whose objectives were to define Australia's HDR resources, the technologies required for a future research program, the economic potential to compete with existing energy extraction methods, and the cost of possible future research paths. The study was funded by the Energy Research and Development Corporation (ERDC), and the salient results of it were presented at the fourth meeting of the HDR working party held at AGSO on 18 August. This meeting was attended by industry partners interested in utilising the energy derived from any successful future research program, and by companies with expertise in carrying part of that research load.

The AGSO study has identified several promising sites in Australia where granites occur at the required depth beneath sedimentary basins containing insulating shale and coal measures, which maintain high geothermal gradients within the basins. These granite bodies are favoured as the sites for establishing stimulated[1] heat-exchange zones in the Earth at temperatures exceeding 250°C. Other continents apparently are poorly endowed with such sites, so Australia could take the lead in developing this untapped energy resource.

AGSO's study also identified another major factor favouring development of HDR in Australia. This factor relates to the stress state of the shallow crust. In other parts of the world where HDR experiments have been performed, with one exception (Sweden) the minimum principal stress direction is horizontal, and reflects a regime of extensional or wrench tectonics. As a result, the zones stimulated by fluid injection (that is, the HDR reservoirs) inevitably were oriented vertically, perpendicular to the minimum principal stress direction. Vertical reservoir geometry has a number of disadvantages — for example, upward-migrating heated water cools moderately quickly; downward-migrating water is inaccessible; and injection and production wells must be inclined to facilitate the generation of, and access to, a series of parallel subvertical reservoirs.

By contrast, in Australia, the minimum principal stress is pervasively vertical (Denham & Windsor 1991: *Exploration Geophysics*, 22, 101–105), and reflects a regime of compressional tectonics. In such a stress regime, the reservoir generated by fluid injection would tend to be horizontal or subhorizontal, as it was for the shallow (450 m) injection experiment at Fjallbacka, Sweden (Jupe et al. 1992: *International Journal of Rock Mechanics Mining Sciences & Geomechanics, Abstracts,* 29, 343–354). Horizontal reservoir geometry would provide optimal heat recovery, and obviate the need for directional drilling. Although injection pressures would have to be higher than in other stress regimes, horizontal reservoir geometry would provide an overall advantage to reservoir engineering. The presence of high horizontal stresses in the Australian crust has been documented by borehole measurements, and is manifested by the occurrence of earthquakes with overthrust mechanisms; many of these events are unusually shallow, and several large historic earthquakes have produced overthrust scarps at the Earth's surface.

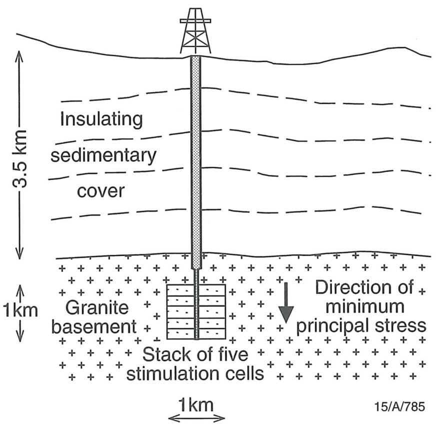

Fig. 1. Configuration of five horizontal reservoir-stimulation cells in a vertical hole penetrating 1.2 km into granite basement where the minimum compressive stress is vertical. The resulting HDR reservoir has a rock volume of 1 km³.

Reservoir growth (by fluid injection) depends on the release of strain stored in the shallow crust. Fluid injection increases pore pressure and counteracts the ambient stresses; it essentially reduces the 'effective stresses', increases the ratio of maximum to minimum stress, and thereby activates rock fractures toward shear failure. Shear failure induced by injection is manifested by swarms of microearthquakes with magnitudes typically less than zero (on the open-ended Richter scale), rupture dimensions of tens of metres, and shear displacements of a millimetre or less. Seismic monitoring is a principal diagnostic tool in HDR reservoir engineering because it provides information on the location of induced microearthquakes, their mechanism, their rupture dimensions, and the amount of shear offset. Thousands of microearthquakes are commonly stimulated by HDR injections.

[1] The rocks would be artificially stimulated to open by shear failure along existing fractures, rather than by the creation of new fractures.

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Self-propping, effected by small displacements of fractures, results in a significant enhancement of permeability. Laboratory experiments on granite samples with fractures offset by 0.5 mm have shown permeability increases of more than four orders of magnitude at effective pressures up to 160 megapascals (Durham & Potter 1994: *Journal of Geophysical Research,* 99, 9391–9399). Permeability increases of three or four orders of magnitude have been inferred from flow tests at HDR sites in the USA, UK, France, and Sweden.

An important step in worldwide HDR reservoir engineering will be the generation of a multiple-reservoir system by injections into a series of open-hole well segments. In a compressional tectonic regime, such as that prevailing in most of Australia, the reservoir-stimulation cells will tend to be oriented horizontally. Multiple cells could be stacked in the hole from the bottom upwards, so that they stimulate large volumes of rock. At sites where HDR stimulation experiments have been carried out elsewhere, seismic monitoring has shown that rock can be stimulated for a distance of over 1 km outwards from the point where it is injected. In principle, a 1-km section of vertical hole could be divided by stacked reservoir-stimulation cells into five sections, each up to 200 m high, to stimulate a reservoir of rock with a volume of 1 km^3 (Fig. 1). Such a large volume of rock at a temperature over 250°C would store enough heat energy to power a 50-megawatt power station for 30 years, before the rock temperature decreased to a level too low for power generation (150°C).

Reports produced for the ERDC study will form the basis of an approach to industry for funds to carry out an injection experiment in Australia. The funds raised would influence the complexity (and cost) of the experiment, which might range from a demonstration of subhorizontal reservoir growth in a moderately deep well (deeper than at Fjallbacka) to the generation of multiple reservoirs in a deep (4 to 4.5 km) hot (250°C) well. Any such experiment would accelerate the development of HDR reservoir engineering. Candidate sites in South Australia, Queensland, and New South Wales are under consideration.

For further information, contact Dr Doone Wyborn or Dr Malcolm Somerville (Division of Regional Geology & Minerals) at AGSO.

Origin and timing of petroleum generation in the Bowen and Surat Basins

AGSO has completed an extensive organic geochemical study of natural gases, condensates, oils, and core samples to delineate the origin, generation, and migration history of petroleum in the Bowen and Surat Basins. Petroleum is almost exclusively sourced from the Permian rocks. The main phase of generation of the gaseous hydrocarbons followed that of the liquid hydrocarbons, and contributed to the mobilisation of the petroleum over long migration distances.

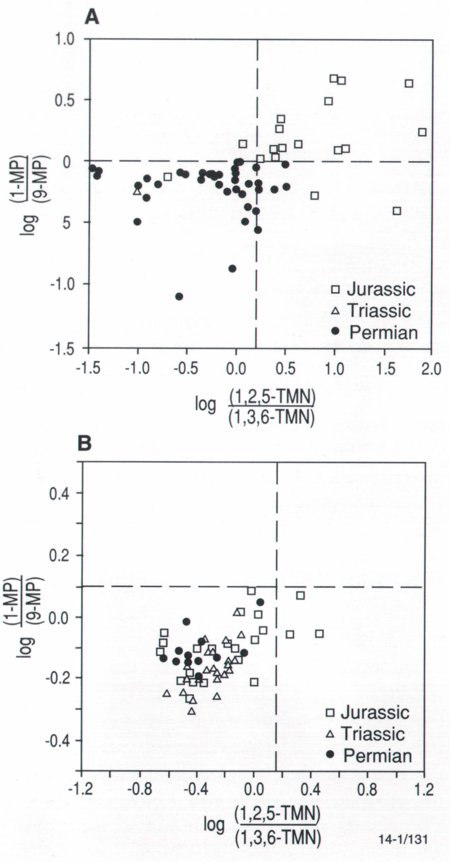

Fig. 2. Aromatic hydrocarbon source plots of 1- / 9-methylphenanthrene versus 1,2,5- / 1,3,6-trimethylnaphthalene for A) sediments and B) liquid petroleum. Data plotting in the top right quadrant (Fig. 2A) indicate a contribution from specific conifer floras that radiated during the Jurassic.

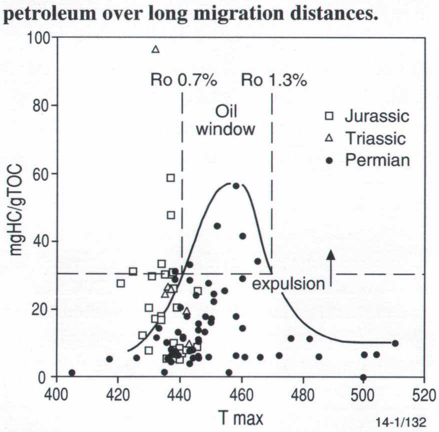

Fig. 3. Plot of sediment extract yield (mg saturated + aromatic hydrocarbons/gTOC) versus Tmax.

Petroleum-to-source-rock correlation

Bulk geochemical parameters of TOC, Rock Eval, and bitumen yield have distinguished potential source rocks for liquids at several stratigraphic levels in the Surat (Jurassic) and Bowen (Triassic and Permian) Basins. Lower-delta-plain coals have a higher hydrocarbon potential than upper-delta-plain coals, and alluvial coals in the Denison Trough also have some liquid potential. Liquid-to-source correlations based on gas chromatographic features are hampered by the effects of widespread biodegradation and the general immaturity of the sampled Triassic and Jurassic section. Saturated tetra- and pentacyclic biomarkers show that the petroleum was sourced mainly from terrestrial organic matter in clastic sediments. However, these biomarkers do not show the resolution required to differentiate terrestrially dominated source rocks of Jurassic to Permian age. By contrast, aromatic biomarkers having strong conifer affinities can distinguish Jurassic from older rocks (Fig. 2A; Boreham 1994: *AGSO Record* 1994/42). This relationship constrains the age for the source of the liquid petroleum to pre-Jurassic (Fig. 2B). Stable carbon isotopes can further distinguish organic matter in Permian rocks from that in the richest Triassic potential source (Moolayember Formation). Thus, the effective source rocks for the liquid petroleum in the Bowen and Surat Basins are almost exclusively the Permian terrestrial rocks; the marine rocks have contributed only minor amounts, and isotopic evidence suggests that a Triassic source has made a local, very minor contribution.

Permian organic matter is also the source of the gaseous hydrocarbons, according to isotopic similarities between iso-butane and Permian kerogen. Carbon dioxide, which can occur in large amounts, has a dual origin: inorganic and microbiological. Inorganic carbon dioxide, presumably generated in the mantle or from the decomposition of carbonates at depth, is isotopically depleted in ^{13}C compared with that derived from microbial biodegradation.

Maturation

For sequences in the Bowen and Surat Basins, we have developed correlations between common maturity parameters — Tmax, extract yields, methylphenanthrene index (MPI), and the optically measured vitrinite reflectance (Ro; Fig. 3; Boreham 1994: *op. cit.*). Combined with measurements of MPI on the liquid petroleum and $^{13}C/^{12}C$ ratio on individual gaseous hydrocarbons, these chemical maturity parameters have allowed source-rock and petroleum maturity to be compared according to a common 'calculated vitrinite reflectance' (Rc) scale; Rc is assumed to correspond to the maturity of the source rock during expulsion. The maturity range for liquid petroleum (oils and condensates) — $0.65\%<Rc<1.05\%$ (Fig. 4; Boreham 1994: *op. cit.*) — corresponds well with the observed 'oil window' between $0.7\%<Ro<1.3\%$ and peak generation at 0.9–1.0% Ro for the Permian rocks (Fig. 3). However, it is quite distinct from the maturity range for gas — between $1.05\%<Rc<1.4\%$ (Fig. 4); this distinction reflects the different times during which the liquid and gas were generated.

For the liquid petroleum, maturity parameters based on saturated tetra- and pentacyclic biomarkers lack clear relationships with aromatic maturity indicators. Similarly, maturity parameters show poor correlations if they are based on different structural types (e.g., hopanes and steranes), but better correlations if they are based on closely

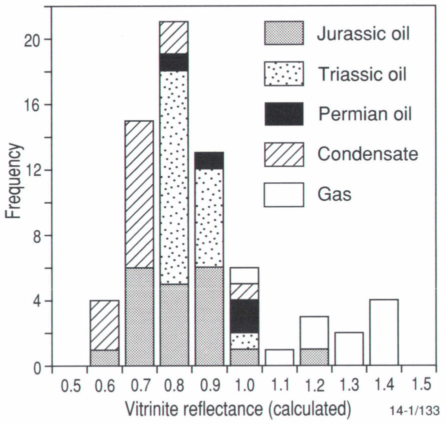

Fig. 4. Frequency plot of 'vitrinite reflectance equivalent' for oils, condensates, and gases.

related structural isomers. These observations reflect the timing of biomarker release, source, and biodegradation effects.

The main phase of gas generation, following the liquid phase, is assumed to have been critical to efficient secondary migration of the liquid petroleum. Gas composition varies systematically with locality; for example, wet gas occurs to the south (on the Wunger Ridge), and is progressively drier to the north (on the Roma Shelf). Although this trend parallels the present-day maturity gradient for the Permian rocks, a correlation between this gradient and gas maturity based on carbon-isotope composition is less well defined. Whether this poor correlation reflects an inadequacy in the method for evaluating gas maturity, or a strong source control for the gas composition, awaits resolution from a continuing AGSO–GSQ study of regional source-rock richness and maturity.

Migration and emplacement of petroleum

A correlation is apparent between reservoir age and Rc. Thus, liquid petroleum in Jurassic reservoirs is generally less mature than that in Triassic reservoirs, which in turn is slightly less mature than that in Permian reservoirs. Petroleum expelled from the effective source rock initially would have been slightly less mature when it entered the secondary migration pathway than that generated and expelled later in the 'oil window'. Jurassic reservoirs, most distant from the 'source kitchen', would have been charged by a 'migration front' of lower maturity.

Biodegradation of petroleum along the secondary migration pathway and in-reservoir has had a major impact on the bulk and biomarker compositions of the petroleum. Oils and condensates from the Bowen and Surat Basins are paraffinic when unaltered, but become naphthenic as a result of biodegradation. At least two phases of biodegradation are apparent. An initial and cosmopolitan phase resulted in heavy biodegradation, which led to the generation of 25-norhopanes. A more restricted final phase of biodegradation followed supplementation of the altered petroleum by a volumetrically superior pristine liquid. The final phase has a gas chromatographic signature showing a progressive loss of light n-alkanes, closely followed by the waxy n-alkanes, and finally depletion of the isoprenoids — pristane and phytane (Fig. 5a–c; Boreham 1994: *op. cit.*). Biodegradation is also recognised in the condensates by a loss of n-alkanes (Fig. 5a), and in the gases by anomalously heavy isotopic compositions of propane and to a lesser extent n-butane.

For further information, contact Drs Chris Boreham or Russell Korsch (Division of Marine, Petroleum & Sedimentary Resources) at AGSO.

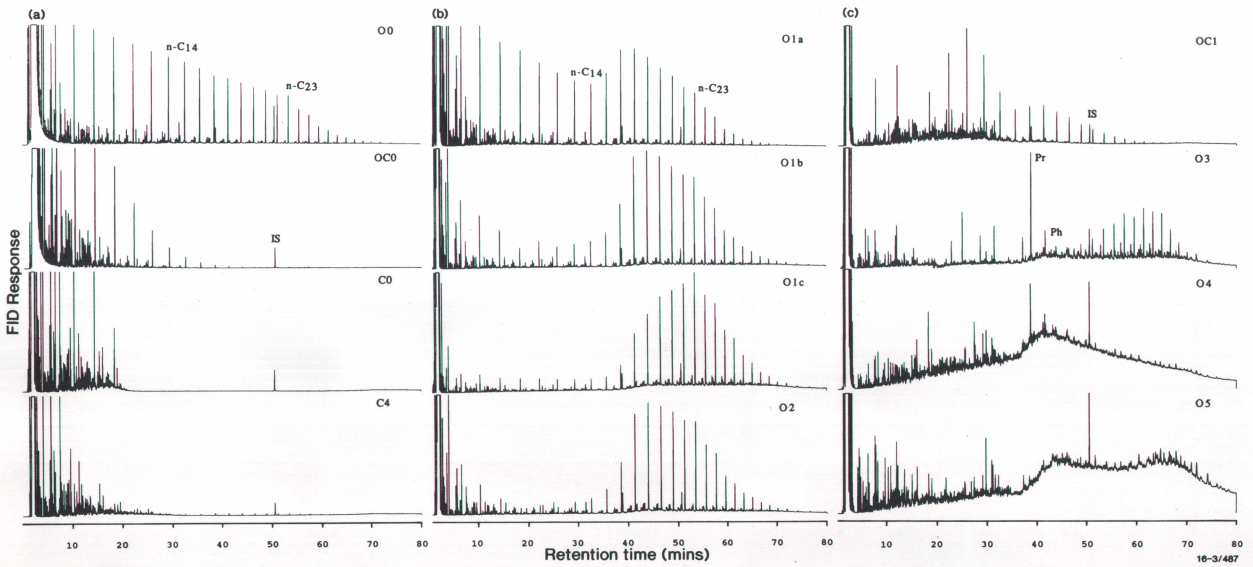

Fig. 5. Representative gas-chromatography traces for oils grouped by their level of biodegradation. O = oil, OC and C = heavy and light condensates respectively; numeric characters refer to the level of biodegradation on a scale 0 to 10: 0 = none, 5 = moderate, and 10 = heavy; a, b and c are sublevels.

Image separation for map production

A workflow explained

Introduction

The use of images embedded in map products has been gradually increasing over the last few years, to the point where it has become an accepted feature of many map series. Images have traditionally been used on their own with limited overlaying information, and also as photographs in the margin of the map sheet. Digitally rectified airphotos and satellite images are increasingly used as backdrops to topographic maps.

AGSO's Cartographic Services Unit (CSU) has been monitoring this trend, with a view to meeting customer requirements in the map products from AGSO. CSU is well placed among its peers because it has an integrated solution for producing maps — from the initial creation of computer-assisted drafting (CAD) and geographic information system (GIS) files through to the generation of lithographic standard film separates on its Mapsetter — and has substantial image-processing capabilities. The challenge has been to integrate the bitmapped images into the map production workflow. The discussion that follows outlines but one method of achieving this integration.

The map project

Having been generating geophysical images for some years, AGSO decided to include the total magnetic intensity and gravity images of the Katherine 1:250 000 Sheet area onto the recently published geological map sheet. The Katherine 1:250 000 geological map is the first of the new, second-generation maps completed under the National Geoscience Mapping Accord.

CSU developed a workflow to meet the requirements for incorporating postcard-size images in the margin of the map sheet. The images were all pseudo-coloured TIFF files generated from the image-processing software. Before they could be separated, their colours had to be calibrated in the software, so that the output prints matched the screen display. The assumption for this first map was that the colours returned from the proof process would be very close to the final print, and that the calibration figures could be refined for subsequent maps in the series.

The software

Several software packages are available to facilitate colour separation, particularly in the illustration and document-publishing sphere. CSU used the following ones for this project:

- MicroStation V4 — the UNIX version of this CAD package was used to create the map sheet in vector format;
- CorelDraw V4 — a PC graphics package that can both manipulate the image for size and masking, and calibrate the colour separation to correct for different output devices;
- Intergraph plotting software with Microstation design file and Postscript file interpreters;
- Intergraph IRASB — raster manipulation and editing software that is used to create the four-colour base files at the required dimensions for the map-publishing phase, and to manipulate the size, orientation, and position of the converted images; and
- Intergraph Map Publisher — generates final map separates for plotting on CSU's Optronics Mapsetter 4000.

The workflow (Fig. 6)

The overview of the workflow is:

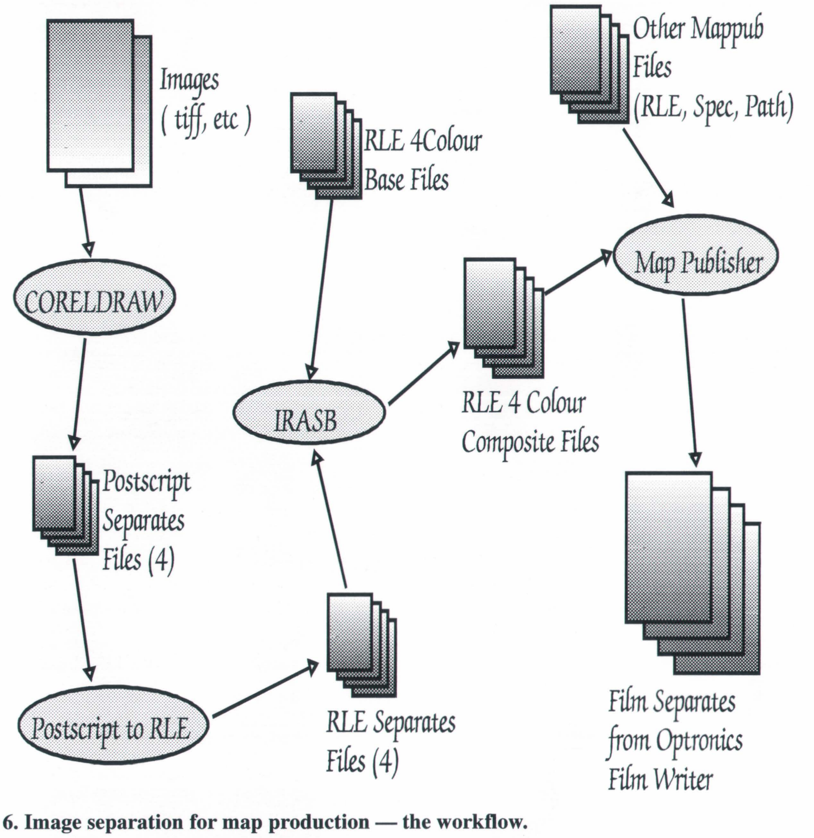

Fig. 6. Image separation for map production — the workflow.

- import image file into CorelDraw, roughly scale the image to the final output size, and crop any areas that overlap; then, using the defined colour calibration for the Optronics film recorder, generate four Postscript separates files;
- move Postscript files to UNIX system and process separately through the Postscript interpreter;
- create four base raster files into which the images will be merged. These bases are the size of the final map sheet, and have registration marks to register accurately the images into their correct position. Merge each of the images with its appropriate base raster file, to create four composite files at the final map size. The images must register exactly, so require careful manipulation; and
- combine these composite files with the other map files for processing by the map-publishing software, to create the film-separates files.

Image set-up and separation

The two images to be added to the map sheet were created in ER Mapper. File transfer protocol (FTP) over the AGSO backbone network facilitated their transfer from AGSO's image-processing system to CSU's PC network.

Having been saved in colour TIFF format in the ER Mapper, both images were imported into CorelDraw as TIFF images. They were roughly scaled to final size, and masked to the required graticule.

The separation of CorelDraw images is incorporated into the printing set-up forms, in which the printer and colour calibration are defined, before each colour is separated as a Postscript file. Each image at the time of separation was created with system-generated registration and crop marks, to allow accurate final alignment on the map.

Converting the image separates

The image-separate files were then transferred to the CSU Intergraph UNIX system, and processed through the Postscript interpreter. While the separates were being converted, four base raster files were created into which the images were to be merged.

Once the base files and image files had all been created, they were moved to a UNIX workstation and manipulated under IRASB. Key registration marks had been placed on the black plate base to allow the aligning of the black image separation into the correct final position on the map sheet. With the help of the registration marks generated by CorelDraw, the other three image separates were similarly manipulated into position on their appropriate base files. When all image files had been saved into the base raster files, then the registration and crop marks were edited from them.

Integration into the map-publishing process

While the work on the images had been proceeding, the rest of the map had been processed from the vector design file into separate raster files for each unique map feature, and screen-proof files of the map created without the images.

The image raster files that had been created through the IRASB processing were moved to the Map Publisher workstation. The map-publishing process generated another screen-proof file, which was checked for integration of the images before the final map plate separates were generated for plotting on the Optronics.

Outcome for AGSO

The workflow outlined above is but one method for integrating small images into the margins of map sheets. It has the advantage that no extra raster file types are generated for integrating into the Map Publisher processing stream, and therefore simplifies the production of final map separates. For most of CSU's Map Publisher operators, the only new functions are the separation in CorelDraw and the conversion from Postscript to RLE.

With the trend toward integrating images into vector-map databases, this has been a useful project. We now have an image-integration procedure that works effectively and results in an enhanced map product.

For further information, contact Colin Wilcox (CSU, Division of Information Services) at AGSO.

Mapping of continental and oceanic crust west and south of Tasmania

In February–March 1994, AGSO surveyed a large area of the seabed south and west of Tasmania (Figs. 7, 8) in waters beyond the continental shelf. The survey, carried out aboard the French RV *L'Atalante*, applied a sophisticated swath-mapping system of a type not available in Australia. Starting in Auckland and finishing in Adelaide, the survey mapped in detail almost 200 000 km² of the Australian continental margin and adjacent abyssal plain (an area three times the size of Tasmania) in water generally in the range 2000–4500 m deep. It also acquired 17 300 km of geophysical data: 3200 km on the transit from New Zealand, 13 600 km on the South Tasman Rise and the west Tasmanian margin, and 500 km on the transit to Adelaide. The cruise involved AGSO scientists, and university staff and students from Australia and France. Three students are writing theses on aspects of the results.

The *L'Atalante* investigation has yielded the equivalent of onshore topographic maps and satellite images, which facilitate the mapping of surface fault patterns — information of considerable interest to petroleum explorers. The maps will also be used to help define Australia's Legal Continental Shelf, which under the UN Law of the Sea Convention will be in place late in 1994.

The *L'Atalante* scientific cruise has provided the latest addition to the database for an area that has been a long-term focus of activity for AGSO (and its predecessor, BMR), largely because of offshore west Tasmania's perceived petroleum potential by analogy with the Bass Strait basins. In 1971, BMR recorded geophysical profiles with a line spacing of 35 km off Tasmania and across the South Tasman Rise, from near the coast to the abyssal plain. In 1985, BMR contributed to collaborative studies of data acquired during two cruises by the German RV *Sonne* — one geophysical, the other sampling — to west Tasmania and the rise. In 1987 and 1989, BMR used RV *Rig Seismic* for two geoscience cruises to the west Tasmanian region.

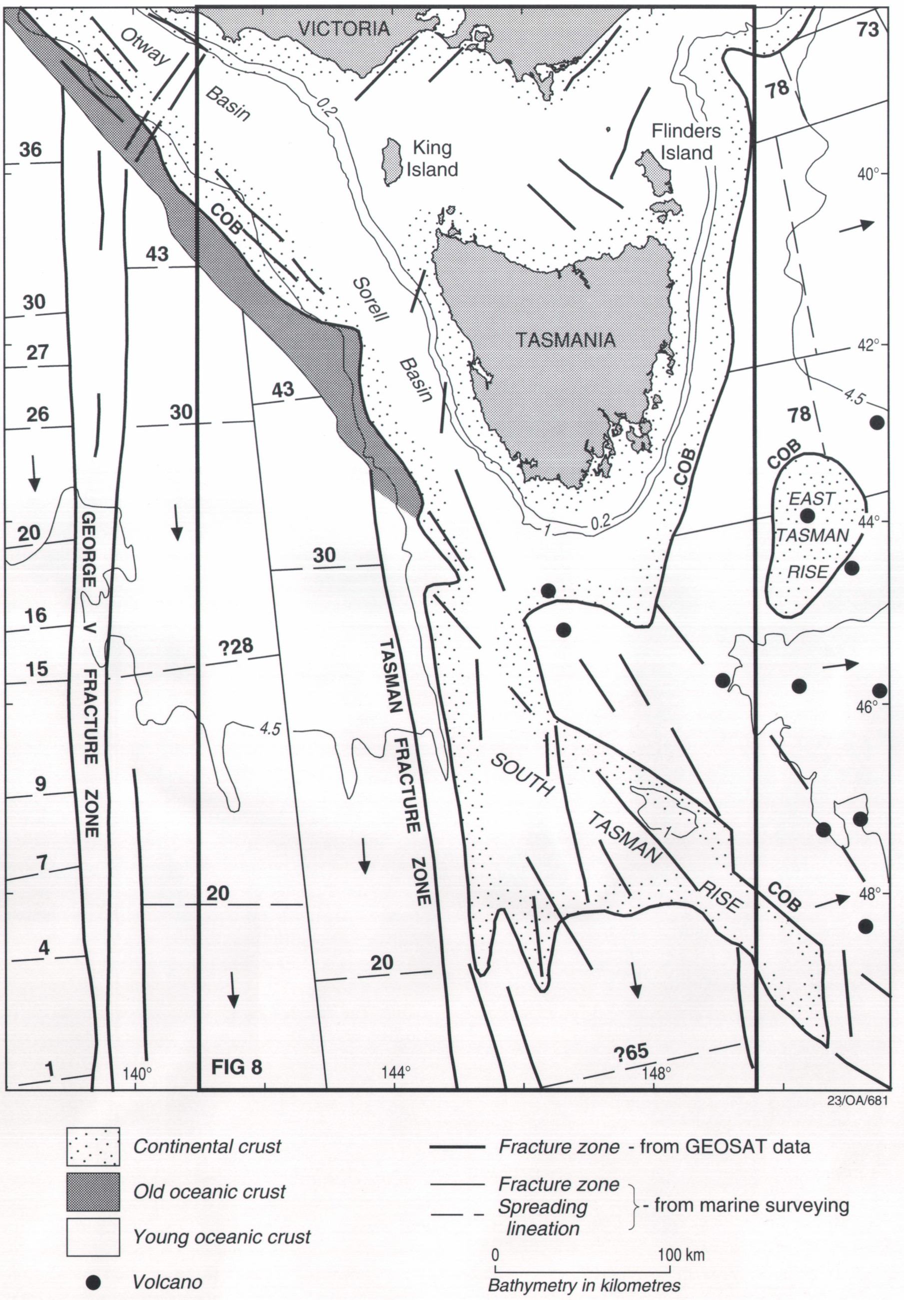

Fig. 7. The tectonic elements of the offshore Tasmanian region as presently known. The position and ages (in millions of years) of magnetic anomalies are taken with some modifications from the 'Tectonic map of the circum-Pacific region, Southwest Quadrant', published in 1991. COB = continent–ocean boundary. Further work by our group will greatly refine this picture.

The entire southern margin of Australia has a structural pattern and geological history that is largely controlled by the separation of Australia and Antarctica. The Sorell Basin west of Tasmania is a prospective southward prolongation of the gas-producing Otway Basin. The offshore Tasmanian region is bounded on three sides by Upper Cretaceous to Palaeogene oceanic basalt crust (Fig. 7), which formed during seafloor spreading between 80 and 20 Ma ago — as the Lord Howe Rise broke away to the east, and Antarctica to the south. Determining how and when Australia and Antarctica split apart, what effects this split had on regional geology, and how the Southern Ocean climate has changed over the last 50 Ma are the main objectives of AGSO's continuing studies following the acquisition of the *L'Atalante* data.

Data acquired from *L'Atalante* shipboard systems

L'Atalante has a Norwegian SIMRAD EM12D multibeam sonar system. During the survey, this system mapped an area up to 22 km wide along each ship track traversed at a speed of nearly 20 km per hour. Equipped with three frequencies around 13 kHz, and 162 narrow sonar beams, which enable it to cover a swath with a maximum total beam angle of 150° athwartships, it outputs bathymetric maps and acoustic imagery in real time. It provided 100 per cent coverage of the seabed in most areas, and generated 1:250 000 maps with 20-m contours.

Six-channel seismic, magnetic, and gravity data were also recorded along all tracks. The seismic reflection profiles penetrate up to 2.5 s (two-way time) below the seabed.

South Tasman Rise and Sorell Basin

The South Tasman Rise, a submerged continental block larger than Tasmania, extends from 44° to 50°S (Fig. 7); the *L'Atalante* survey mapped about 150 000 km² (three-quarters) of it. The rise sank completely below the ocean only in the last 20 Ma, and parts of it are less than 1000 m deep. Spectacular faults and giant fault blocks occur in water depths of 2500–4500 m on its western and eastern sides (Fig. 8). In the west, the submarine cliffs, dwarfing anything in Australia, rise 2300 m high, and have average slopes of up to 15–20°. The rise consists of about 20 per cent outcropping rock and 80 per cent sediment cover. Ancient schist, gneiss, and granite, Palaeozoic and Mesozoic sedimentary rocks, and Tertiary basalt have been dredged and cored. The rise is current-swept, and Neogene sediment cover is thin.

The geology of the South Tasman Rise surely rivals that of Tasmania in complexity. Its basement rocks are separated by deep, narrow sedimentary basins bounded by strike-slip faults trending 345° and 320°. The basins, coupled with geochemical evidence from surface samples that thermogenic hydrocarbons are being generated, offer promising prospects for petroleum exploration.

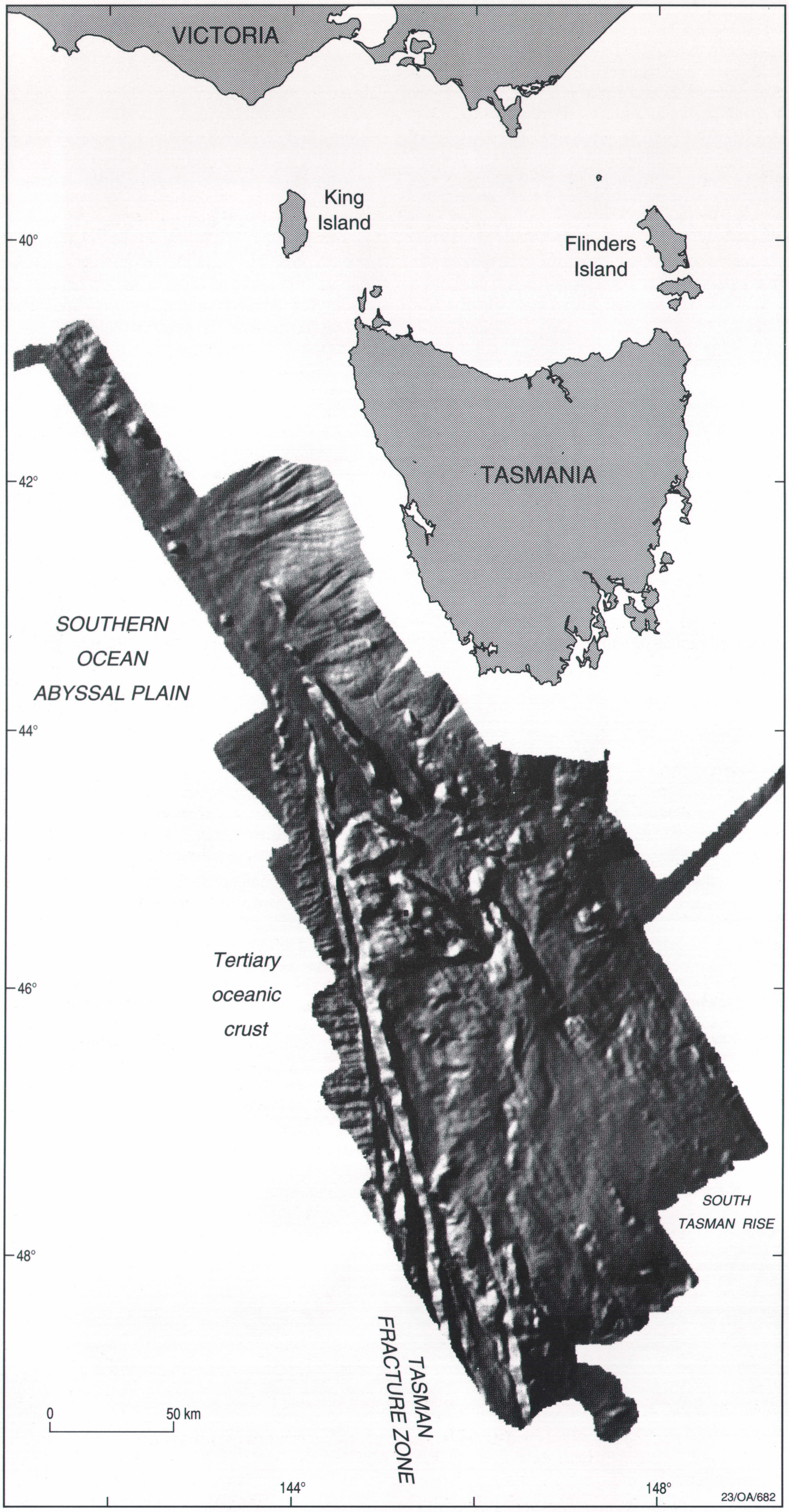

Fig. 8. Relief diagram of the region surveyed. Water depths are in the range 1000–4500 m. Note the older 320° and the younger 345° fault directions, the volcanic cones, and the canyons west of Tasmania. The seafloor-spreading fabric is visible at the seabed as easterly trending ridges.

The *L'Atalante* survey also mapped an area of about 50 000 km^2 of the Sorell Basin. In contrast to the South Tasman Rise, this area was heavily sedimented in Tertiary times, so deep structure is less apparent at the surface. On the continental shelf, basement blocks separate four sub-basins containing more than 3000 m of Cretaceous and Tertiary strata, much like those in the Otway Basin. Similar thicknesses are present on the continental slope. Some basin-forming faults were imaged on the lower slope, including a fault scarp — 2500 m high and trending 320° — containing Cretaceous shallow-marine rocks. Sedimentary thicknesses, oil and gas shows, and some structuring suggest that the basin has considerable petroleum potential.

Recent studies of cores from west of Tasmania, by Vicky Kosslow at the Australian National University, suggest that in the last 100 000 years mudflows have dominated deposition on the upper slope to about 2300 m, whereas the lower slope has received turbidites and debris flows. This sedimentological pattern is supported by our swath-mapping data, which show submarine canyons extending from the upper slope to the abyssal plain. Our data suggest that the canyons are eroding the 4–5° upper slope, but allowing deposition below 2300 m, where the slope decreases appreciably.

Australia–Antarctica break-up

The oceanic basalts on the abyssal plain, 4500–5000 m deep west of Tasmania and around the South Tasman Rise, and the magnetic anomalies associated with them, record much of the history of the separation of Australia and Antarctica. Antarctica started to move slowly past Tasmania 130 Ma ago, and finally cleared it at about 40 Ma. Thereafter, what had been dry land or a shallow-marine embayment west of Tasmania subsided thousands of metres below the sea, as did the South Tasman Rise.

Early stretching between Antarctica and Australia apparently formed the major strike-slip faults trending 320°; the faults trending 345° reflect a later change in the direction of relative movement between the two continents. When the direction changed is not certain, but the prevailing dogma is that it coincided with seafloor spreading at about 95 Ma; another possibility is 45 Ma. Spreading was very slow until about 45 Ma, and much faster thereafter. The later movement formed the western and southern margins of Tasmania and the South Tasman Rise. Their eastern margins formed differently, when the Lord Howe Rise moved away to the east-northeast from 85 to 55 Ma. The southern and northern margins of the South Tasman Rise formed by stretching, a process that involved both strike-slip and normal faulting. A saddle that formed as a result of this process is at least 3000 m deep between Tasmania and the rise, where the crust has moved along faults trending 345°. Associated volcanoes are 600 m high; 70 of them constitute a volcanic field about 100 km south of Tasmania in the fishing grounds of an important deep-trawl fishery.

At 40 Ma ago (when Tasmania and Antarctica had cleared one another), the easterly flowing Circum-Antarctic Current, which had flowed north of Australia, broke through in the south, and caused major oceanographic changes, including easterly flowing currents. A pile of sediment more than 1000 m thick that has accumulated east and south of the South Tasman Rise was probably swept from the rise by these currents. The oceanic abyssal plain west of the rise is lightly sedimented; the swath-mapping shows that the surface topography mimics that of the oceanic basement (Fig. 8), and slow-growing manganese crusts are widespread on the sediment surface.

Future work

The geophysical data gathered on the cruise are being integrated with other remotely sensed data, to define better the history of the separation of Australia from Antarctica to the south and the Lord Howe Rise to the east. The L'Atalante maps are proving invaluable for planning a 1994 seafloor-sampling cruise by *Rig Seismic*. Several reflection seismic profiles are also planned to cross the region; recorded in conjunction with profiles proposed for the National Geoscience Mapping Accord project in Tasmania, these should show the crustal structure to 20–30 km below the seabed, and help reveal how this complex region formed. Our colleagues from the University of Paris in Villefranche-sur-Mer intend to apply for use of the deep-diving submersible *Nautile*, to sample the strata exposed in the cliffs flanking the abyssal plains and thereby improve our understanding of the geology of the fault-bounded continental blocks.

For further information, contact Dr Neville Exon or Mr Peter Hill (Division of Marine, Petroleum & Sedimentary Resources) at AGSO.

Sulphur-undersaturated magmatism — a key factor for generating magma-related copper–gold deposits

Copper–gold deposits have, in the last few years, become the major mineral exploration target in eastern Australia and the Asia–Pacific region. Such deposits are favoured because the prices of their two commodities tend to be inversely correlated, thus guaranteeing profitable returns in any economic climate. Additionally, these deposits tend to be large; they include some of the world's largest gold and copper resources in a single mine (Grasberg, Porgera, Murun Tau). Geochemical studies of igneous rocks associated with copper and gold deposits in the Lachlan Fold Belt have led to the recognition of some critical features of the magmatism from which such mineralisation developed.

Sulphur-undersaturated source rocks

The most important magma characteristic that ultimately leads to the development of a mineralising system is the relationship of melt-fraction sulphur content to the level of sulphur saturation.

Sulphur saturation results in the removal of both copper and precious metals from the magma because of their large distribution coefficients (2000 for Cu and up to 10^5 for precious metals) between sulphide and melt (Peach et al. 1990: *Geochimica Cosmochimica Acta*, 54, 3379–3389). These elements then no longer can take part effectively in magmatic fractional crystallisation processes and fluid evolution. Therefore, for the development of a magmatic Cu–Au deposit, the magma must remain sulphur-undersaturated throughout its magmatic evolution.

As sulphur solubility increases, so the capacity of a melt to be saturated diminishes. Oxygen fugacity has the greatest effect on sulphur solubility, but temperature and magma composition are also important. The sulphur solubility in tholeiitic basalt at QFM oxygen buffer is about 1000 ppm. The sulphur solubility of andesitic liquid at QFM is 500 ppm, but reaches 2000 ppm at HM buffer (Carrols & Rutherford 1987: *Journal of Petrology*, 28, 781–801), wherein much of the sulphur is dissolved as the oxide species (anhydrite component). Basaltic magmas derived from asthenospheric melting are sulphur-saturated (1000 ppm; Czamanske & Moore 1977: *Geological Society of America, Bulletin* 88, 587–599), consistent with their formation by around 20 per cent partial melting of a mantle source containing around 250 ppm S (Sun et al. 1991: *Precambrian Research*, 50, 1–35), of which 50 ppm or less S remains in the residue. These magmas also contain low Au (1 ppb) and Cu (70 ppm; Hertogen et al. 1980: *Geochimica Cosmochimica Acta*, 44, 2125–2143; Hamlyn et al. 1985: *Geochimica Cosmochimica Acta*, 49, 1797–1811), as the bulk of these elements is retained in sulphide droplets in the residual mantle.

Most granites are also likely to be sulphur-saturated. Reduced S-type granites commonly contain early-formed accessory pyrrhotite (Whalen & Chappell 1988: *American Mineralogist*, 73, 281–296), and hence are sulphur-saturated. I-type granitic magmas are commonly more oxidised, and thus can contain higher sulphur contents before saturation occurs. Increasing oxidation states of I-type granites correlate with a greater propensity for copper and gold to be partitioned and retained in their melts, and, consequently, with more prospect of fluid evolution being copper- and gold-rich. A good example of a sulphur-undersaturated, but sulphur-rich I-type granite is the oxidised Braidwood Granodiorite in the Lachlan Fold Belt of southeast New South Wales (Wyborn 1985: *BMR Record* 1985/34, 21–23). This granite has yielded over 1 000 000 oz gold from zones of sulphide-rich hydrothermally altered granodiorite, and from placer deposits derived from erosion of the granodiorite. However, most I-type granites are not as oxidised as the Braidwood Granodiorite and are sulphur-saturated.

Calc-alkaline volcanics are commonly high in sulphur (e.g., Whitney 1984: *American Mineralogist*, 69, 69–78; Bornhorst & Rose 1986: *Journal of Geology*, 94, 412–418; Hattori 1993: *Geology*, 21, 1083–1086). The primary magmatic sulphur content of some of these volcanics, however, is hard to resolve, because large amounts of sulphur are degassed from the magma during ascent and eruption (Moore & Fabbi 1971: *Contributions to Mineralogy & Petrology*, 33, 118–127; Wallace & Carmichael 1992: *Geochimica Cosmochimica Acta*, 56, 1863–1874; Alt et al. 1993: *Earth & Planetary Science Letters*, 119, 477–494). Some of this sulphur comes from subducted altered oceanic crust and sea water, as evidenced by positive sulphur-isotope values (Woodhead et al. 1987: *Earth & Planetary Science Letters*, 83, 39–52; Alt et al. 1993, *op. cit.*), and some comes from convecting asthenosphere above the subducted slab. Most of these volcanics are not highly oxidised and are sulphur-saturated. The presence of sulphide inclusions in early formed minerals indicates that immiscible sulphide melts were present before degassing, and that the magmas were sulphur-saturated.

The most common magmas, from both mantle and crustal sources, are mostly sulphur-saturated, and are unlikely to produce gold (or copper)-rich fluids after fractional crystallisation.

Mantle-lithosphere source for large gold-rich porphyry-style magmas

The one magma source-rock that is ideal for the formation of high-gold, sulphur-undersaturated magmas is the Earth's mantle lithosphere. A large part of the lithosphere already has been depleted in sulphur by the removal of a sulphur-saturated basaltic melt at an earlier time. This earlier sulphur-saturated melting event would have left behind a small amount of sulphide which would be highly enriched in copper and gold and other precious metals. But what is the mechanism for extracting a melt fraction from this sulphur-poor refractory material?

Supra-subduction-zone wet melting to produce boninitic magmas can extract the remaining sulphides left in the mantle lithosphere (Hamlyn & Keays 1986: *Economic Geology*, 81, 1431–1445), but these magmas are restricted in their capacity to fractionate and evolve a fluid phase at high levels in the crust. Metasomatism, by whatever process, of the refractory mantle lithosphere provides the key to melt extraction. A metasomatised source will lower the liquidus of the lithosphere, so that melting will occur when appropriate tectonic conditions prevail — such as thermal perturbation, lithospheric delamination, or pressure reduction due to a rearrangement of plate geometry. The resultant magma will be commonly high in incompatible elements and, in modern environments, not directly related to contemporaneous subduction systems. Such magmas commonly fall in the fields of trachybasalt or shoshonite in an alkali–silica diagram.

Most of the magmas appear to have been of this type during the Ordovician magmatism in the Lachlan Fold Belt in New South Wales (Wyborn 1992: *Tectonophysics*, 214, 177–192), where the most potassic magmas provided the best sources of mineralisation. There are several reasons why such potassic magmas make the best mineralising sources:

- a high concentration of potassium implies that the mantle lithosphere source is intensely metasomatised and therefore in an optimum state (requiring low liquidus temperatures) for contributing a large volume of melt, which in turn will favour sulphur-undersaturation and enable large magma bodies to rise into the crust;
- water is probably more abundant in a more-metasomatised source mantle, and, ultimately, more water will be available for fluid evolution;
- the presence of low-melting-point potassic phases increases the likelihood of fractional crystallisation — by the process known as convective fractionation (Sparks et al. 1984: *Philosophical Transactions of the Royal Society of London*, A310, 511–534) — in upper crustal magma chambers; and
- a high alkali content in the magma increases the intrinsic Fe^{3+}:Fe^{2+} content of the magma (Sack et al. 1980: *Contributions to Mineralogy & Petrology*, 75, 369–376; Kilinc et al. 1983: *Contributions to Mineralogy & Petrology*, 83, 136–140; Kress & Carmichael 1991: *Contributions to Mineralogy & Petrology*, 108, 82–92), thus favouring the development of magnetite and anhydrite over pyrrhotite, and increasing the sulphur solubility of the melt; this in turn will result in a greater likelihood of the

magma being sulphur-undersaturated.

Although shoshonites theoretically make the best magma sources for Cu–Au mineralisation, less potassic examples are not uncommon (Bougainville, Batu Hijau, Copper Hill). A sulphur-undersaturated mantle source at Copper Hill (Lachlan Fold Belt, NSW) is still clear; indeed, the Nd-isotopic systems indicate that the magma there (εNd = +7.3; Wyborn & Sun 1993: *AGSO Research Newsletter* 19, 13–14) was derived from an even more primitive source than adjacent more-potassic mineralising systems. The Copper Hill magma probably originated from a more weakly metasomatised part of the mantle lithosphere than the adjacent, more potassic magmas associated with the North Parkes and Cadia porphyry deposits. Thus, large, low-alkali systems can still give rise to major Cu–Au deposits provided that they are undersaturated in sulphur, able to fractionate, and rich enough in water to evolve a fracture-forming fluid phase at high levels in the crust.

Precious-metal fractionation in a sulphur-undersaturated magma derived from metasomatised mantle lithosphere

Ordovician magmatic rocks from the Lachlan Fold Belt display all the chemical characteristics indicating sulphur-undersaturated fractionation of magmas derived from a metasomatised mantle lithosphere. Most of these rocks retain a normal mantle ratio of Pd:Au of 4:1, and display incompatible behaviour of these elements during fractionation (Wyborn 1990: *BMR Research Newsletter* 13, 8). However, platinum behaves compatibly, and its high concentration in early-formed olivine cumulates probably reflects early crystallisation of Pt–Fe alloy (90% Pt). This alloy has been observed as an early-formed phase in Alaskan-type complexes (Johan et al. 1989: *Mineralogy & Petrology*, 40, 289–309), and precipitated in experiments by Amosse et al. (1990: *Chemical Geology*, 81, 45–53). The divergent behaviour of palladium and gold on the one hand, and platinum on the other, provides irrefutable evidence of fractionation at sulphur-undersaturated conditions, the necessary requirement for later development of a Cu–Au mineralising system.

Analyses of Pt and Pd at the ppb level provide an excellent method of determining whether a mantle-derived magma system is sulphur-saturated or not.

Alteration haloes around mantle-derived Cu–Au mineralised intrusions

The likely low water contents of Cu–Au-bearing magmas derived from metasomatised mantle lithosphere, and, especially their low sulphur content, will give rise to rather inconspicuous alteration haloes: potassic alteration can be confined to the immediate margins of quartz-vein sets, and iron sulphide is uncommon. Such alteration products are insignificant as exploration targets for either geochemical or electrical techniques. However, the high Fe^{3+} content of both magmatic rocks (particularly potassic ones) and vein systems, leads to the widespread development of both magmatic and hydrothermal magnetite, and thus to a large dependence on magnetic properties for exploration.

Copper(%):gold(ppm) ratios in mantle-derived Cu–Au deposits

The estimated primordial mantle contents of copper and gold are 30 ppm and 1 ppb respectively (Sun et al. 1991: *Precambrian Research*, 50, 1–35); hence, the mantle ratio Cu(%):Au(ppm) is 3:1. First-stage melt extraction from the mantle at sulphur-saturated conditions will extract copper preferentially to gold, because gold is more chalcophile and copper is more lithophile; it therefore decreases this ratio somewhat in the residual mantle lithosphere. Second-stage melting and fractional crystallisation in a sulphur-undersaturated state will progressively decrease this ratio even further as copper is admitted into early crystallising magnesium–iron silicates, whereas gold will be an incompatible element dissolved in the magma. Most porphyry Cu–Au systems have ratios around 1:1, which is entirely in accord with this model. Cu–Au skarns tend to have higher Cu:Au ratios than their associated porphyry deposits, but the ratio is still much less than 3:1, generally around 2:1.

The Cu:Au ratio of many deposits is consistent with derivation of the magmatic source in the mantle, and with a gradual decrease of the ratio through the processes of partial melting, fractionation, fluid evolution, and mineral deposition. However, this does not imply that all deposits with similar ratios are necessarily derived in this way.

Tectonic environments

The hypothesis developed here is that second-stage melting of metasomatised mantle is the main source of Cu–Au magmas because it is the most likely process to generate sulphur-undersaturated conditions. These conditions, however, would be influenced by the tectonic environment in which the melting were taking place. Thus, an active subduction zone associated with the melting would be likely to contribute sulphur from the subducted oceanic crust, and from asthenosphere convecting in the mantle wedge. For this reason, the absence of contemporaneous subduction arguably is an important criterion for the development of optimum sulphur-undersaturated conditions. Indeed, studies have shown that mineralisation has occurred away from the influence of subduction-related processes (for example, in the western Pacific; Ahmad et al. 1987: *Economic Geology*, 82, 345–370; Richards et al. 1990: *Geology*, 18, 958–961), and so too has shoshonitic magmatism (Johnson et al. 1978: *Tectonophysics*, 46, 197–216; Gill & Whelan 1989: *Journal of Geophysical Research*, 94(B4), 4561–4578).

Subduction-related magmatism makes exploration difficult, because it generates an abundant variety of non-prospective sulphur-saturated rocks through which explorers need to search to find the prospective rocks — as in the western Pacific island arcs. This difficulty can be overcome by good geological mapping and petrological analysis. However, in some environments, the lack of subduction-related magmatism facilitates a rapid assessment of prospective magmatic centres. For example, in the Lachlan Fold Belt (NSW), the magmatism apparently was not due to subduction (Wyborn 1992: *Tectonophysics*, 214, 177–192) and was sulphur-undersaturated, and all the Ordovician magmatic centres are considered prospective. A more detailed study of these centres will reveal whether extensive fractional crystallisation took place, and if hydrothermal alteration products and secondary magnetite developed. The products of other magmatism in the Lachlan Fold Belt (NSW) — the widespread Silurian volcanics — are unprospective because they are derived from the melting of pre-existing continental crust, and are sulphur-saturated.

Elsewhere, in intracratonic regions such as the Cretaceous of the lower Yangtze Basin, China (Xu 1990: *Geological Society of America, Special Paper* 237), focus of studies by AGSO for comparison with the Ordovician igneous rocks of the Lachlan Fold Belt in New South Wales, magmatism was associated with an abundance of mineralisation, and many of the magmatic centres are probably prospective. These and other magmas not obviously related to subduction originated in a tensional or transtensional environment which favoured melting, and in which major fractures apparently accessed the mantle lithosphere.

Good mapping, and a good petrological understanding of the types of magmatism, help immensely to focus exploration effort on particular magmatic centres, particularly in regions where unprospective sulphur-saturated magmatic rocks are the dominant rocks exposed at the surface.

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Vulcan Sub-basin, Timor Sea

Clues to the structural reactivation and migration history from the recognition of hydrocarbon seepage indicators

Introduction

The region underlying the Timor Sea, located on the northwestern Australian margin south of the island of Timor (Fig. 9), is one of Australia's most promising hydrocarbon provinces. It is a structurally complex region with a multiphase tectonic history spanning the Early Ordovician to the Miocene. Collision between the Australian and Eurasian plates in the Late Miocene transformed the margin from a Mesozoic passive to an oblique collisional setting. Throughout the long history, geological events have produced a number of sub-basins, platforms, and grabens with a range of ages, orientations, and structural styles. The resultant complex overprinting of one structural grain by another dominates the region, has produced complex geometries, and hinders tectonic interpretation.

The exploration history in the Timor Sea reflects the complexities described above. After early initial successes from drilling the most obvious structures in the early to mid-1980s (the Jabiru, Challis, and Skua discoveries in the Vulcan Sub-basin), a large number of dry holes were drilled from the mid-1980s until the early 1990s. More significantly, many of these 'dry' holes intersected residual oil columns (such as Avocet 2 and Gargarny 1). The palaeo-oil columns in these wells were probably breached as the structures were reactivated during the onset of collisional tectonism in the Late Miocene.

A number of non-commercial gas accumula-

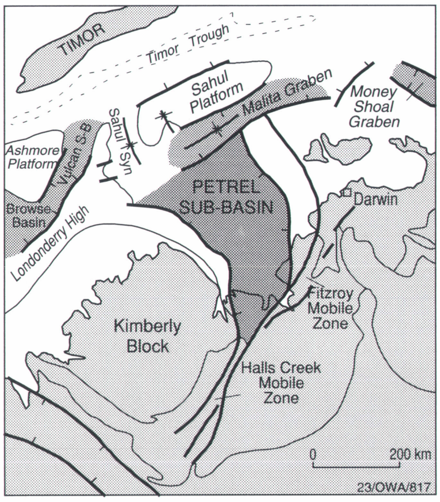

Fig. 9. Location map showing the tectonic elements of the Timor Sea, northwestern Australia.

tions, many with associated thin oil legs, have also been encountered; in several of these wells, an earlier oil leg has been displaced subsequently by gas.

The recent discovery of oil at Elang 1 and Laminaria 1 on the western margin of the Sahul Platform has refocused the attention of explorers, and highlighted the exploration potential of the Timor Sea. Nevertheless, future success in the Timor Sea will depend on developing an improved understanding of the structural reactivation and hydrocarbon migration/remobilisation history.

Present study

In collaboration with several exploration companies, AGSO has been carrying out research to constrain the hydrocarbon migration and remobilisation history of the region. To date, this research has focused principally on integrating regional water-bottom geochemical ('sniffer') and seismic data with the results of detailed geochemical (including carbon- and oxygen-isotope) studies of representative wells. Soon, more detailed well-log, biostratigraphic, seismic (structural and stratigraphic), fluid-inclusion, diagenetic, source-rock, and oil-geochemical studies will complement those already undertaken.

The preliminary aspects of this study have focused on the nature and significance of carbonate cementation in the shallow-marine Eocene sandstone (Grebe Formation) of the Vulcan Sub-basin. Within localised areas of the sub-basin, these sands are strongly cemented with calcite, which produces shallow zones of anomalously high seismic velocity (i.e., seismic 'pull-up') and attendant problems in the delineation of both the structure and the reservoir distribution in the underlying (hydrocarbon-prospective) Mesozoic section. As these cemented zones (and their associated seismic anomalies) are closely associated with two of the major fields in the Timor Sea (Skua and Jabiru), this problem has important commercial ramifications. The cemented zones are generally areally restricted (200–600 m wide and up to 3000 m long), and commonly but not exclusively spatially associated with major underlying fault systems.

Previous work on these cemented zones suggested that they formed diagenetically during subaerial exposure in the Oligocene. However, published investigations from the US Gulf Coast have shown that surficial and near-surface carbonate cementation is commonly associated with the oxidation of migrating hydrocarbons. The co-occurrence of the cemented Eocene sandstones in the Vulcan Sub-basin with major oilfields and fault systems implies that the cementation there might also be due to hydrocarbon oxidation. A sampling and analytical strategy was developed to investigate this possibility.

Results and conclusions

Four exploration wells that drilled through the strongly cemented Eocene sandstones were selected for study: Keeling 1, Skua 3, Jabiru 2, and East Swan 2. Detailed carbon- and oxygen-isotope, mineralogical, petrographic, and major-element analyses were completed for each well. The carbon-isotope analyses are particularly sensitive discriminators of the origin of the carbon in carbonate cements. For example, 'normal' marine carbonate cements are typically in the range –2 to +2 $\delta^{13}C$ $^0/_{00}$. In contrast, the carbon in methane is more typically –38 to –42 $\delta^{13}C$ $^0/_{00}$. Consequently, according to the simple reaction:

$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$ .... *reaction 1*

carbonate cements that have formed via the oxidation of migrating hydrocarbons will have carbon-isotope values closer to that for methane than that for 'normal' marine cements — that is, they will be much more negative.

The down-well carbon-isotope profile for the carbonates and carbonate cements in East Swan 2 well (Fig. 10) is representative of all of the wells

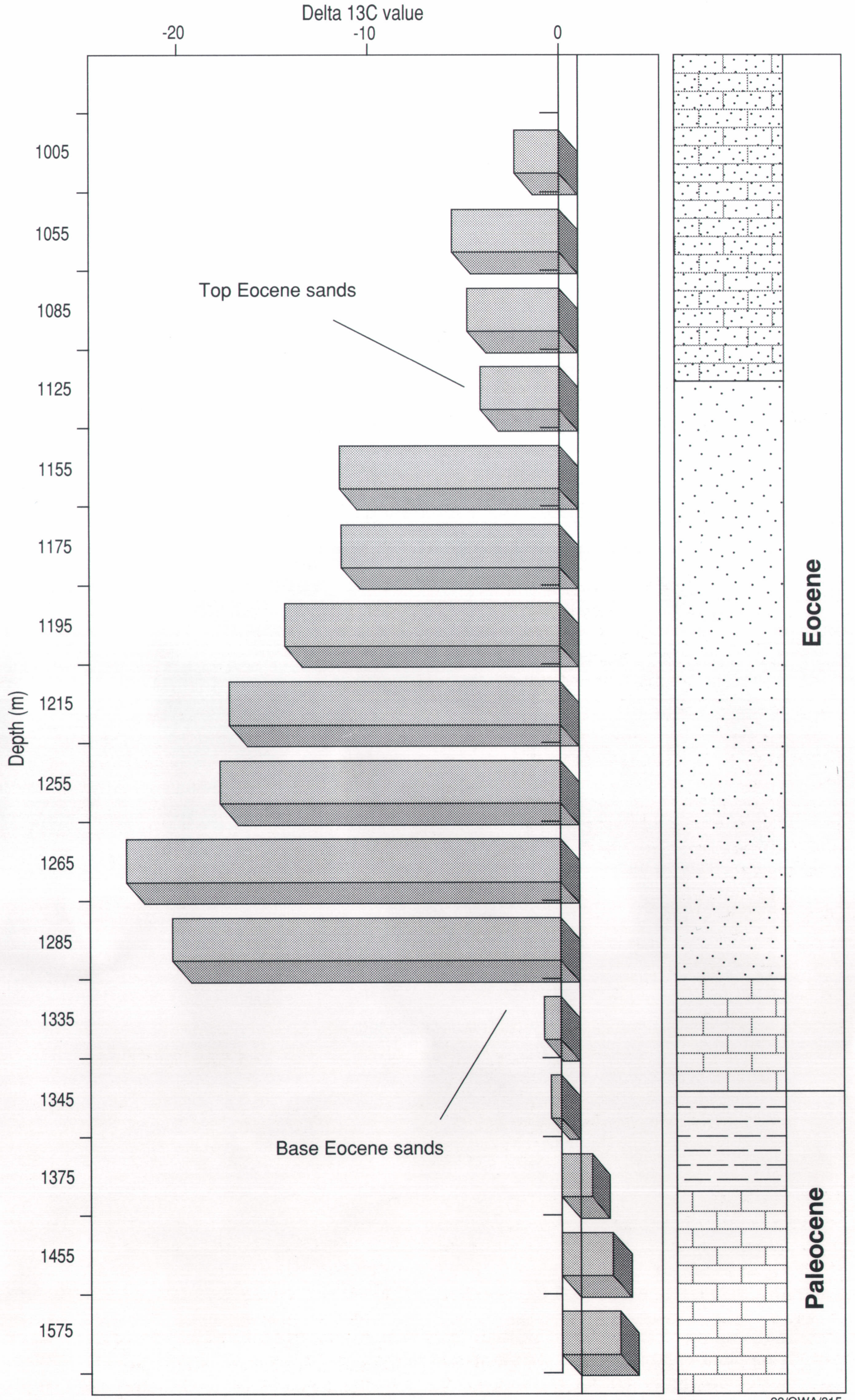

Fig. 10. Down-well carbon-isotope profile for the East Swan 2 well, Vulcan Sub-basin, Timor Sea.

studied. The carbon-isotope compositions of the carbonate is 'normal' above the cemented Eocene sands, then shows a strongly negative excursion through the cemented sands, where it peaks at almost –25 $\delta^{13}C$ $^0/_{00}$ towards the base. Below the Eocene sands, the carbon-isotope values change sharply to slightly positive. Mineralogical and petrological studies have shown that the carbonates within the cemented sands are secondary pore-filling cements which consist principally of calcite, accompanied in places by ankerite representing an apparently later subsidiary phase. Cross-plots of the ^{13}C values versus major-element and mineralogical compositions have shown that the most isotopically negative $\delta^{13}C$ values are found within the cleanest (most SiO_2-rich) sands. These observations suggest that the most porous and permeable sands were the most prone to carbonate cementation.

The carbon-isotope values in the strongly cemented sands (Fig. 10) are diagnostic of carbonate cements formed principally via the oxidation of hydrocarbons, according to reaction 1 (above). Such values are similar to those reported from the US Gulf Coast, and approach those obtained from hydrocarbon well gases in the Timor Sea region. Consequently, these cemented sands delineate zones of hydrocarbon seepage — not subaerial weathering during the Oligocene, as previously proposed. These zones are effectively 'hydrocarbon-related diagenetic zones' (HRDZs), and their development is illustrated diagrammatically in Figure 11.

Support for this proposal comes from the results of AGSO's sniffer study in the Vulcan Subbasin (O'Brien et al. 1992: *BMR Record* 1992/62). Areas of present-day hydrocarbon seepage from the sea-floor — such as near the Skua oilfield, the East Swan 2 well, and southeast of the Montara wells along the Vulcan Sub-Basin/Londonderry High boundary zone — are invariably closely associated spatially with zones of strongly cemented Eocene sands; that is, areas of modern-day seepage always have HRDZs associated with them. In contrast, some areas of known Tertiary hydrocarbon seepage (as indicated by large residual oil columns) — such as around the Avocet and Gargarny 1 wells on the Eider Horst — showed no sniffer anomalies, but did contain strongly cemented Eocene sandstones. These observations probably indicate that all the hydrocarbons were lost from the Eider Horst in the Late Miocene, and that the area is no longer receiving hydrocarbon charge.

The establishment of a causal relationship between the carbonate-cemented Eocene sandstones and hydrocarbon seepage from the underlying section clearly has potentially important implications for the exploration industry. For example, determination of the areal distribution of the cemented zones, as defined by seismic mapping, could provide a useful exploration aid in delineating hydrocarbon migration pathways; the presence of an HRDZ over an individual prospect would effectively eliminate the risk on hydrocarbon charge.

Determining the presence or absence of HRDZs and/or sniffer anomalies over prospects also provides an indication of seal integrity. The seismic expression of HRDZs above structures which have leaked completely (East Swan 2, Avocet 2) are much stronger and more obvious than those associated with the Jabiru and Skua oilfields. Moreover, seismic mapping has shown that, in residual oil accumulations such as East Swan 2, the Callovian and Miocene trends are markedly oblique to one another, which perhaps facilitated the breaching of the trap. In contrast, the Callovian and Miocene trends show only slight obliquity over the Jabiru and Skua oilfields, suggesting that the integrity of these structures was largely (but, as evidenced by the presence of HRDZs, not completely) maintained during reactivation, and hence they were less prone to leakage.

There appears to be a continuum between high-integrity accumulations which have leaked little (if at all), and strongly reactivated accumulations which have spilled completely. Examples of the former include Montara, Keeling, Skua, and Jabiru, whereas the latter include East Swan 2 and the wells on the Eider Horst.

Consequently, integrating seismic structural mapping with the seismic-expression characterisation of the HRDZs should help us determine not only whether an individual structure is ever likely to have had a hydrocarbon column but whether that column is still likely to be preserved.

Future directions

This work is a logical extension of AGSO's interpretation of the regional geological frame-

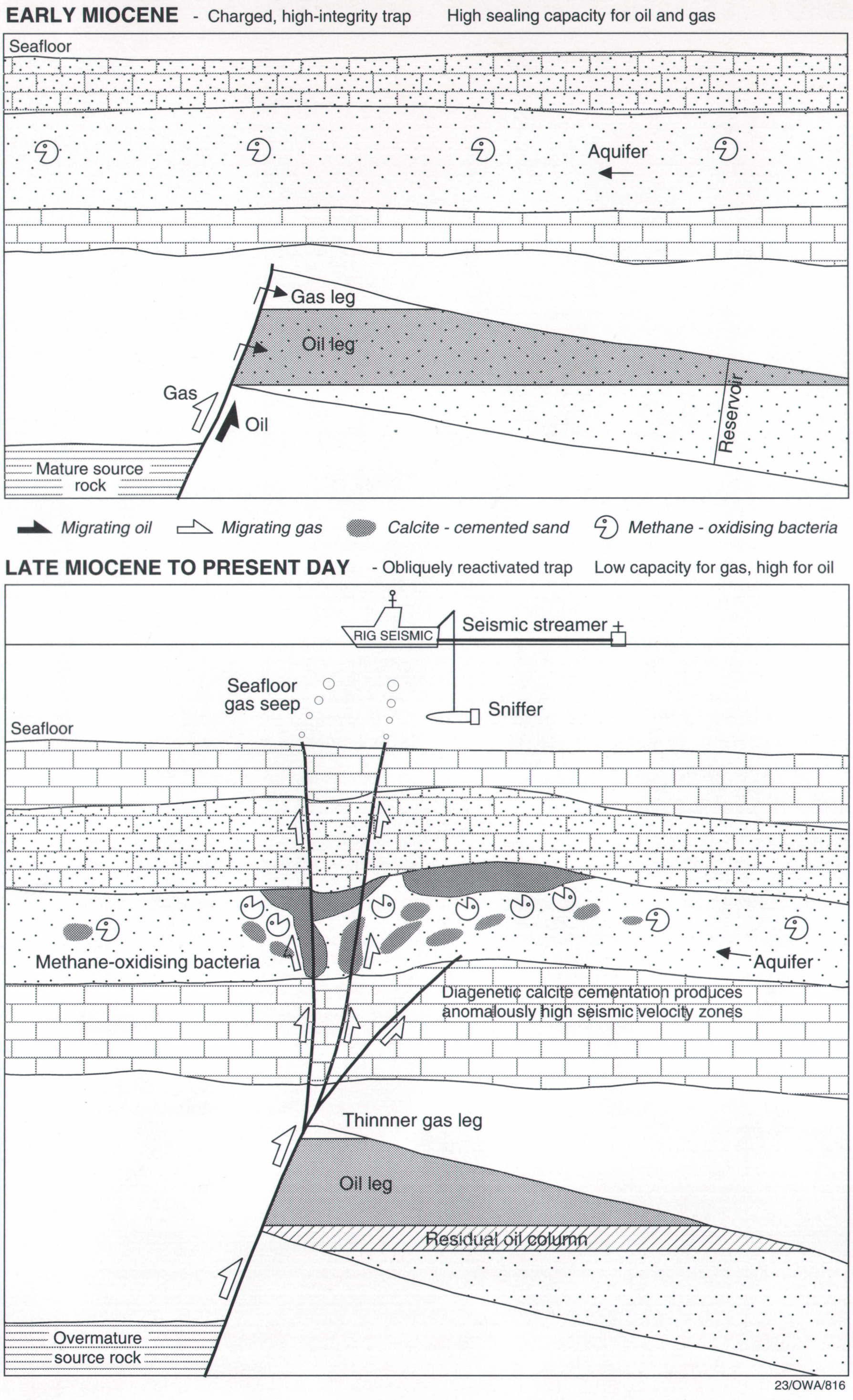

Fig. 11. Diagram showing the transition from a high-integrity oil and gas accumulation, to a reactivated and partly breached accumulation in the Late Miocene. Leakage of gas up the faults provides an energy source for methane-oxidising bacteria within the Grebe Formation aquifer. The released carbon dioxide is incorporated into pervasive carbonate cements along the fault zone and within localised Eocene closures.

work of the North West Shelf. This regional study, which is based upon the integration of AGSO regional deep seismic reflection and aeromagnetic data with conventional industry data, has provided an understanding of the structural architecture and reactivation history of the Timor Sea region. This understanding has, in turn, provided the stratigraphic and structural environment within which the more detailed observations on migration pathways and reactivation history, as discussed in this article, can be made.

AGSO hopes to establish a series of semi-quantitative criteria with which to evaluate and rank individual petroleum prospects in the Timor Sea. Our ultimate goal is to improve exploration efficiency and, thereby, to contribute to further exploration successes in the region.

For further information, contact authors Dr Geoffrey W. O'Brien (Division of Marine, Sedimentary & Petroleum Resources) at AGSO, or Mr Phil Woods at Norcen International Pty Ltd (Sydney).

A proposed extensional transfer structure in the Archaean of the Eastern Goldfields

Komatiite[1]- and peridotite-rich sections in the Eastern Goldfields Province constitute time-rock markers (cf. Claoue-Long 1990: *Third International Archaean Symposium, Extended Abstracts*, 355–356; Rattenbury 1993: *AGSO Record* 1993/54, 73–75) for establishing tentative but testable correlations of greenstone and 'whitestone' associations. The rocks so correlated appear to represent a stratigraphically and structurally plausible framework that is consistent with limited SHRIMP (sensitive high-resolution ion-microprobe) U–Pb (zircon) geochronological data. Further, the distribution of probably equivalent komatiites in the north of the province facilitates the identification of a moderately well-defined zone of aeromagnetic trends as the successor to an early (D_E) extensional transverse discontinuity[2].

Oversby & Whitaker (1994: *AGSO Research Newsletter*, 20, 17–18) described this aeromagnetic zone as trending almost due north, obliquely across the fictional 'Keith–Kilkenny Lineament' and most of the preserved adjacent high-strain greenstone–'whitestone' corridor of the Keith–Kilkenny Tectonic Zone. The course of the zone is marked locally by the old Goanna Patch group of gold workings, and by sectors of the Clifford and Minatichi Faults (Oversby & Whitaker, *op. cit.*, fig. 19). The zone cannot be confidently traced through magnetically near-homogeneous material (probably undeformed granitoid rocks) immediately south of the east-central Leonora 1:100 000 Sheet area, although it lines up well with an aeromagnetic extension of the exposed Moriarty Shear only about 25 km farther south (Fig. 12). Even though the trend of the Moriarty Shear as currently named swings into alignment with the northwest-trending Menzies Shear south of the intersection of the two, about 80 km north-northwest of Kalgoorlie, vestiges of the transverse structure farther south again, to beyond Norseman, are apparent in near-north-trending alignments of the Bardoc Shear, Abattoir Shear, and Mission Fault.

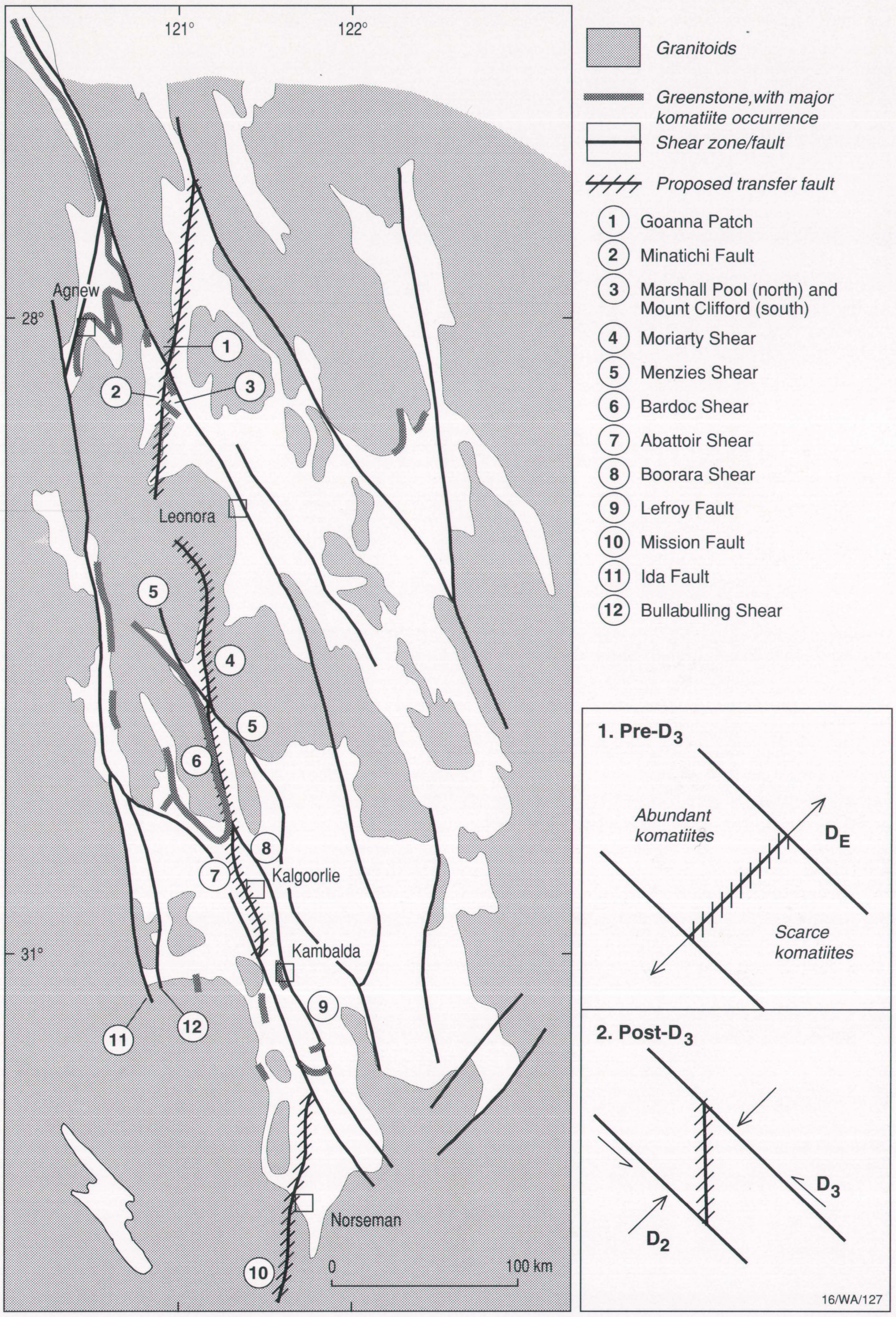

Fig. 12. Simplified geological map showing the locations of major komatiite units in the area between Norseman and Agnew, the course of the proposed transfer structure, and other features mentioned in the text.

AGSO's seismic traverse to the north of Kalgoorlie (Goleby et al. 1993: *AGSO Record* 1993/15) shows the Bardoc Shear to be one of a few dislocations traceable to a depth of more than 10 km; the other two main ones, the Ida Fault and Bullabulling Shear, are both near-north-trending and interconnected along strike.

The original D_E transverse discontinuity is inferred to have had its trend modified, and to have been diffused and locally obliterated, by substan-

[1] Komatiite is the extrusive equivalent of peridotite — i.e., an ultramafic lava containing 18 wt per cent MgO or more on an anhydrous basis, and commonly with distinctive spinifex and other textures (Viljoen & Viljoen 1969a, b: *Geological Society of South Africa, Special Publication* 2, 55–85, 87–112; Donaldson 1982: in 'Komatiites', *Geoge Allen & Unwin, London*, 213–244; Smith & Erlank 1982: in 'Komatiites' *George Allen & Unwin, London*, 347-397).

[2] Such discontinuities separate areas undergoing different amounts or rates of extension; they can significantly influence provenances, types, and thicknesses of accumulating rocks, and thereby control stratigraphic contrasts between adjacent extending areas. Transfer structures are fundamental transverse discontinuities that affect both hanging walls and footwalls of master (i.e., orogen-scale) detachment systems; accommodation structures are confined to hanging walls. Hybrid transverse structures, as their name suggests, involve variable components of transfer and accommodation (e.g. Bosworth 1985: *Nature*, 316, 625–627; Lister et al. 1986: *Geology*, 14, 246–250; Schmitt et al. 1993: *Geological Society of America, Abstracts with Programs*, 5, 143).

tial contraction, rotation, and 'smearing-out' owing to later compression (mainly D_2) perpendicular to, and strike-slip (mainly D_3) movement along, the conspicuous northwesterly structural grain of the Eastern Goldfields (which might reflect the trend of early extensional structures). Qualitative palinspastic restoration — by reversing D_3 sinistral movements, then opening out D_2 compression (Fig. 12 inset) — rotates the discontinuity clockwise, back from its now-oblique orientation relative to the conspicuous northwesterly structural grain, to a trend more nearly orthogonal to the grain.

In the north, voluminous komatiite flows hosting major nickel sulphide deposits (Agnew area; e.g., Hill & Barnes 1990: *Third International Archaean Symposium, Excursion (8) Guidebook*, 361–397; Hill & Gole 1990: *Australasian Institute of Mining & Metallurgy, Monograph* 14, 557–559; Dowling & Hill 1992: *Australian Journal of Earth Sciences*, 39, 349–363) are common in the greenstone–'whitestone' stratigraphy west of the perceived transverse discontinuity. Similar rocks (but with smaller-volume flows and insignificant nickel occurrences) also crop out immediately to the east of the discontinuity (Marshall Pool, Mount Clifford; Barnes et al. 1974: *Geological Survey of Western Australia, Annual Report for 1973*, 59–79; Hill & Barnes *op. cit.*). These rocks are rare farther southeast.

As representatives of essentially unmodified mantle melts, voluminous komatiite flows were presumably fed exceedingly rapidly to the palaeosurface by deep mantle-tapping conduits (Viljoen & Viljoen 1969c: *Geological Society of South Africa, Special Publication* 2, 275–296; Smith & Erlank *op. cit.*; Nisbet 1982: *in* 'Komatiites', *George Allen & Unwin, London*, 501–520). This suggests that, in separating komatiite-rich and effectively komatiite-free areas, the postulated transverse dislocation was an equally deep (i.e., transfer) structure.

Voluminous komatiite flows with major nickel deposits in the Kalgoorlie–Kambalda area significantly lie mostly on the western side of the Moriarty Shear, and to the west of the transverse structure's discerned continuation via the Bardoc and Abattoir Shears and Mission Fault farther south (cf. Hill & Gole *op. cit.*; Cowden & Roberts 1990: *Australasian Institute of Mining & Metallurgy, Monograph* 14, 567–581). If a north-trending connection between the Boorara Shear and Lefroy Fault to the north of Kambalda (Fig. 12) is also considered as a possible associate (displaced segment or splay?) of the structure, the geographical restriction of the rocks and mineral deposits in relation to it is even more impressive.

Spatial and/or temporal contrasts in the distribution of voluminous komatiites, particularly those hosting major nickel deposits, may be especially indicative of transfer structures because of the likelihood that the generation, ascent, and extrusion of these lavas were controlled by a specific and limited range of (extensional) tectonic conditions. A sudden disappearance of such rocks suggests a sharp termination of such special conditions, as at a structural 'bulkhead'. Also, irrespective of whether or not the komatiites define a single isochronous level (although it seems likely that the voluminous ones do), these rocks are such distinctive units that they should also be useful for identifying and evaluating stratigraphic variations associated with inherently more deformable accommodation structures, and the accommodation components of hybrid structures.

Extensional transverse dislocations of all kinds have at least as much potential for explaining observed stratigraphic and structural contrasts in the Eastern Goldfields as do 'terranes' juxtaposed by Phanerozoic-type convergent plate-tectonic processes. Such dislocations might have contributed to the distribution of some gold and other early deposits in addition to nickel.

For further information, contact Dr Brian Oversby (Division of Regional Geology & Minerals) at AGSO.

'Dynamic data exchange' connections to MicroStation from an Excel spreadsheet

Introduction

The release of MicroStation Version 5 provides AGSO's Cartographic Services Unit (CSU) with the capability of using the 'Dynamic data exchange' (DDE) features of Microsoft Windows compliant software to write Excel spreadsheet data into a MicroStation design file. The advantage of this process is that Excel spreadsheet data can be used by an Excel macro to pass a series of MicroStation key-in commands directly to the design file. This process is similar to user commands, but furnishes the added power to manipulate the data in the spreadsheet.

The macro described below was developed to test the process of DDE linkage for inputting coordinate data into MicroStation, since this is a growing requirement where databases and computer-assisted drafting (CAD) systems are not linked through geographic information systems (GISs). Coordinate data supplied to CSU for placing symbols representing natural hazards on a map sheet provided the impetus for developing this technique.

Caveat

The process of making the connection to MicroStation from Excel was, to my knowledge, undocumented, and I have deduced the procedure after examining an example spreadsheet and macro provided by Intergraph, Australia. The process requires a sound knowledge of macro programming under Excel, and assumes a good knowledge of MicroStation key-in commands.

The spreadsheet

Below is a sample of the data set loaded as an ASCII text file and reformatted in Excel:

Ref.	*Lat.*	*Long.*	*Txt long.*	*Txt lat.*	*Data set*
1	18.221	122.123	122.123	18.221	xy=122.123,18.221
1	17.31	121.1	121.100	17.310	xy=121.100,17.310
1	17.146	120.98	120.980	17.146	xy=120.980,17.146
1	16.33	120.55	120.550	16.330	xy=120.550,16.330
1	15.828	120.805	120.805	15.828	xy=120.805,15.828

The 'Ref.' column was taken from the original data, and is a selector for the cell to be placed in the design file. The 'lat.' and 'long.' columns are the original data rearranged for clarity and modified for N–S hemispheres. The 'Txt lat.' and 'Txt long.' columns are calculated columns to fix the numbers from the 'Lat.' and 'Long.' columns into three decimal-place text fields. The 'Data set' column is the final make-up of the point coordinate data that are passed, as a text string, to MicroStation.

The formulas used in the spreadsheet are:

Ref.	*Lat.*	*Long.*	*Txt long.*	*Txt lat.*	*Data set*
1	18.221	122.123	=FIXED(C2,3,TRUE)	=FIXED(B2,3,TRUE)	="xy="&D2&","&E2
1	17.31	121.1	=FIXED(C3,3,TRUE)	=FIXED(B3,3,TRUE)	="xy="&D3&","&E3
1	17.146	120.98	=FIXED(C4,3,TRUE)	=FIXED(B4,3,TRUE)	="xy="&D4&","&E4
1	16.33	120.55	=FIXED(C5,3,TRUE)	=FIXED(B5,3,TRUE)	="xy="&D5&","&E5
1	15.828	120.805	=FIXED(C6,3,TRUE)	=FIXED(B6,3,TRUE)	="xy="&D6&","&E6

The function that cannot be seen from these columns is that the 'Data set' column has been named with the DEFINE NAMES command of Excel for use as a reference within the macro. This column has been called 'Data_Range'.

The Macro

The macro (Table 1) has three columns: the first has only the word 'chan' in the second row; the second identifies the macro commands; and the third lists the comments.

'=INITIATE', '=EXECUTE', and '=TERMINATE' are the only three commands used for DDE connections to MicroStation. Whereas these commands are basically explained in the Excel function reference manual, the strings needed to fill the parentheses are not.

The INITIATE command shown in the macro is the standard way of communicating with MicroStation. The INITIATE command opens a channel or path between the two applications (Excel and MicroStation), and returns a number to reference that channel. That channel number is important to all other commands sending information to MicroStation, and must be captured in a variable for later use. This is done by defining a name for the cell containing the INITIATE command, and this defined name becomes the variable to which the channel number is returned. I have chosen the defined name 'chan', which appears in each of the following EXECUTE commands.

The EXECUTE command uses only two fields: the channel number to communicate with MicroStation, and a text string in double quotes for the MicroStation key-in command. The four EXECUTE commands following the INITIATE command set up the environment for me to place some cells in a lat./long. design file.

The next few commands are strictly Excel macro commands, and carry out operations on the spreadsheet and its data. The FOR.CELL command is the start of a 'for' loop structure that

Table 1. The Excel macro

	macro PlaceCell	
chan	=INITIATE("Ustn","Keyin")	Open connection to ustn — defined name of chan for cell b2
	=EXECUTE(chan,"mark")	Mark design file
	=EXECUTE(chan,"ACT UNITS MU")	
	=EXECUTE(chan,"attach library c:\cell\haz.cel")	Attach cell library — full path to avoid problems with default
	=EXECUTE(chan,"place cell absolute")	Execute place cell command
	=FOR. CELL("cur_cel",SWQUADVO.XLS!Data_Range,TRUE)	Loop for selected range from worksheet
	= DEFINE.NAME("Selector",OFFSET(cur_cel,0,-5))	Define the cell in 'Ref.' column for the current row as the selector
	= IF(Selector=1)	Start IF test on the defined selector
	= EXECUTE(chan,"ac=1")	Select cell to place
	= ELSE.IF(Selector=3)	Next test on defined selector
	= EXECUTE(chan,"ac=3")	Select cell to place
	= ELSE.IF(Selector=4)	Next test on defined selector
	= EXECUTE(chan,"ac=4")	Select cell to place
	= ELSE.IF(Selector=5)	Next test on defined selector
	= EXECUTE(chan,"ac=5")	Select cell to place
	= ELSE.IF(Selector=6)	Next test on defined selector
	= EXECUTE(chan,"ac=6")	Select cell to place
	= ELSE()	Default cell placement if not caught above
	= EXECUTE(chan,"ac=cross")	Select cell to place
	= END.IF()	End of testing
	= EXECUTE(chan,cur_cel)	Pass xy values to ustn in variable cur_cel
	=NEXT()	Get next xy pairs from worksheet
	=TERMINATE(chan)	Close connection
	=RETURN()	Close macro

will cycle through a specified range of cells. The DEFINE.NAME command uses the variable for the current data cell, 'cur_cel', to find the corresponding data cell from the 'Ref.' column, which is the selector for the element to be placed in the design file.

From here on the macro contains an IF–ELSEIF–ENDIF structure which uses the 'Selector' variable to set the active cell to be placed in the design file. When a match is found for any of the selector statements the execution of the macro drops to the ENDIF and continues. The EXECUTE command at the end of the IF–ELSEIF–ENDIF structure passes out the "xy=..." data for MicroStation to place its cell.

The NEXT() statement is the end of the FOR.CELL loop and will return to the start if any more data cells exist in the 'Data_Range'. The TERMINATE(chan) command closes the connection between Excel and MicroStation, and the RETURN() command closes the macro.

The benefits

In the past, coordinate data had to be converted to a fixed format before it could be processed by an AGSO software application to produce the required MicroStation design file. This was a task which needed to be customised each time, because data files were rarely presented in a standard format, and therefore required the resources of a programmer.

Excel simplifies the process of importing data into MicroStation. The tools available in Excel allow quick and efficient formatting of the data, and a macro can then be written to send the data to MicroStation. This technique provides the flexibility to handle any coordinate data, and reduces the level of expertise needed.

For further information, contact Colin Wilcox (CSU, Division of Information Services) at AGSO.

The Mount Stavely Volcanic Complex, western Victoria: mainland equivalents of the Tasmanian Cambrian Mount Read Volcanics

Recent field mapping and geochemical and geochronological studies by AGSO in collaboration with the Geological Survey of Victoria, and the Universities of Tasmania and Latrobe, have shed new light on the nature of the region straddling the Lachlan and Adelaide Fold Belts in western Victoria. The Mount Stavely Volcanic Complex is one of a series of discontinuous greenstone sequences, collectively referred to as the Stavely Greenstone Belt, lying within the Stawell Zone in western Victoria (Fig. 13). The age of the rocks within the zone has been a point of contention owing to the absence of palaeontological and isotopic data. The volcanic complex has been variously interpreted as either a para-autochthonous Cambrian unit within the Lachlan Fold Belt, or as part of the Late Proterozoic–Cambrian Adelaide Fold Belt.

The complex comprises a mildly deformed and low-grade sequence of lavas and volcaniclastic and intrusive rocks which are interbedded, faulted against, and surrounded by quartz-rich turbidites of the Glenthompson Sandstone (part of the St Arnaud Group). Both units share similar structural and metamorphic histories: a phase of folding — which generated north-northwesterly trending upright folds — accompanied by very low-grade burial metamorphism.

The nature and modal abundances of the phenocryst assemblages differentiate four main petrographic groups of lavas in the complex (porphyritic non-vesicular andesite, clinopyroxene-phyric andesite, dacite–rhyolite, and rare hornblende andesite) in addition to hornblende-bearing intrusions and serpentinite. The geochemistry of these lavas reflects an orogenic andesite association, implying that they were erupted either in an island-arc setting or on an active continental margin. However, interbedded submarine sedimentary rocks — including quartz-rich sandstone — and continental-sourced detrital zircons occur in the andesite sequence; they suggest that eruptions were at least in part submarine, and that the complex represents either a high-K orogenic andesite suite erupted in a mature arc built on moderately thin continental-margin crust, or a post-collisional high-K calc-alkaline andesite suite.

New U–Pb zircon analyses, undertaken by AGSO as part of the National Geoscience Mapping Accord, indicate a crystallisation age of 495 ± 5 Ma (Late Cambrian) for the Towanway Tuff metadacite, a unit in the upper part of the Mount Stavely Volcanic Complex. A 501 ± 9 Ma age obtained from detrital zircons in a mafic volcaniclastic rock in the same unit places an older limit on its deposition, but is also likely to directly date an earlier part of the sequence.

These ages indicate that the Stawell Zone is part of the Lachlan Fold Belt, rather than an eastward extension of the Adelaide Fold Belt. Their similarity to ages recently obtained for the Mount Read Volcanics, western Tasmania (Perkins & Walshe 1993: *Economic Geology*, 88, 1176–1197), strengthens the correlation between the two units that previous workers (e.g., Crawford 1988: *In* 'Geology of Victoria', *Geological Survey of Australia, Victorian Division*, 37–62) have based on geochemical, mineralogical, and lithological similarities. Like the Mount Read Volcanics, the Mount Stavely Volcanic Complex also can be interpreted as the products of a Late Cambrian post-collisional volcanic arc.

The Mount Read Volcanics constitute one of the most highly mineralised sequences in Australia. They host several major polymetallic (Cu, Pb, Zn, Ag, and Au) volcanic massive sulphide (VMS) deposits. The correlation of the Mount Stavely Volcanic Complex with the Mount Read Volcanics, supported by the results of this study, significantly upgrades the potential of the complex and the other parts of the Stavely Greenstone Belt as hosts to similar and significant volcanogenic massive sulphide deposits. Volcanic rocks of a similar age or slightly younger in the Tasman Fold Belt of northeast Queensland (Mount Windsor Volcanics and Balcooma Metavolcanics) also contain economic mineral deposits.

Although the Mount Stavely Volcanic Complex has not yielded any economic deposits, it and other components of the Stavely Greenstone Belt do have considerable base- and precious-metal potential. Their full potential, however, has not been evaluated, as much of the belt is covered by a thin veneer of Cainozoic rocks of the Murray Basin, and is yet to be seriously explored.

More detailed information is available in a paper by Stuart-Smith, Crawford, Black, & Bucher, recently submitted for publication in the *AGSO Journal of Australian Geology & Geophysics*.

For further information, contact Drs Peter Stuart-Smith or Lance Black (Division of Regional Geology & Minerals) at AGSO.

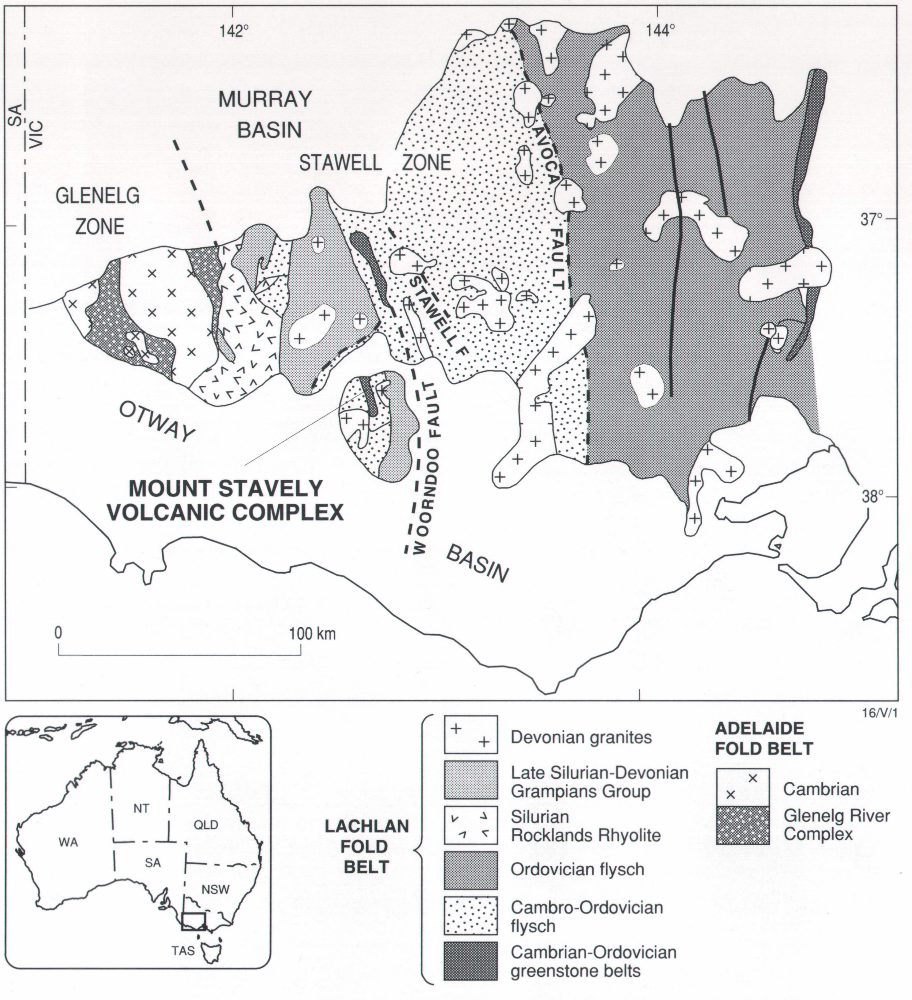

Fig. 13. Location and regional setting of the Mount Stavely Volcanic Complex.

Continued from p. 15

- *At EFB, fluid activity (KFD) at ~1.5 Ga.* This overprint is of wide regional extent: it is found in the basal McArthur Group (*MASO*), southeast McArthur Basin, and as a complete regional metamorphic remagnetisation of dykes (*IM*) in the Mount Isa Inlier.
- *Fluid activity at ~1.6 to ~1.55 Ga (KFB), which correlates well with the age (1.65–1.55 Ga) of uranium deposits in the Alligator Rivers Uranium Field, ARUF, and their metasomatic alteration haloes (~1.6 Ga).* In its role as a pathway for large-scale fluid movement, the Kombolgie Formation figures prominently in some models of the genesis of these deposits. Our interpretation of this overprint supports fluid transport at this time. The overprint is well-developed in the McArthur (*EMMO1*, *AMEO2*) and Nathan Groups (*BDBO*), southeast McArthur Basin.
- *At southeast EFB, post-tectonic dyke intrusion (KFA_i, KFA_h) at ~1.68 Ga.* The overprint is ascribed to a now-eroded east-northeasterly trending dyke, one of many such dykes in the area. It is a neat example of how palaeomagnetism can be used to date now-eroded igneous rocks using the baked-contact zone of the host. Dated dykes of this age have not been recorded from the northwest McArthur Basin, although basic dykes intruding the Ranger uranium deposit, ARUF, have been interpreted as feeders to the ~1.69 Ga Oenpelli Dolerite.
- *Tectonism (KFA_b, KFA_f) in the outlier basins — EFB, GSS — at ~1.68 Ga.* This event is precisely constrained because the component that defines it occurs as both a prefolding and post-folding magnetisation. The poles are in close proximity to the pole for the Mallapunyah Formation (*MAL*) of the lower McArthur Group, southeast McArthur Basin.
- *Activity at GSS at ~1.71 Ga (KFO), which correlates with contemporaneous regional magmatism.* The pole agrees well with overprint poles from the Hobblechain Rhyolite (*HRO*) and Packsaddle Microgranite (*PMGO*), Tawallah Group, southeast McArthur Basin, which are correlatives of the West Branch Volcanics.

Conclusions

In the northwest McArthur Basin, magnetic overprinting in the Kombolgie Formation yields a new awareness of geological events that is unobtainable by other methods. It dates the timing of folding in the outlier basins. It suggests that an older period (~1.68 Ga) of dyke activity is present than has hitherto been recognised, and demonstrates an alternative method of dating now-eroded dykes intruding the Kombolgie Formation. It also neatly illustrates that through magnetic overprinting we have a sensitive *temporal* and *spatial* tracer of fluid passage, as demonstrated by the detection of several episodes of fluid movement through the Kombolgie. Magnetic overprinting may thus have a potential role to play in mineralisation studies and the characterisation of plumbing systems. Not only can fluid activity be detected, dated numerically, and timed relative to tectonic phases, but also its provenance can be established — whether local or regional, focussed or pervasive. Under favourable circumstances, magnetic overprints could be used as a proxy for dating geochemical overprints. Pilot follow-up palaeomagnetic studies in the McArthur Basin are exploring the new possibilities opened up by the discovery of the overprints, particularly their relationship to mineralisation.

For further information contact Dr John Giddings (Palaeomagnetism Group of the Division of Geophysical Observatories & Mapping) at AGSO.

Continued from p. 16

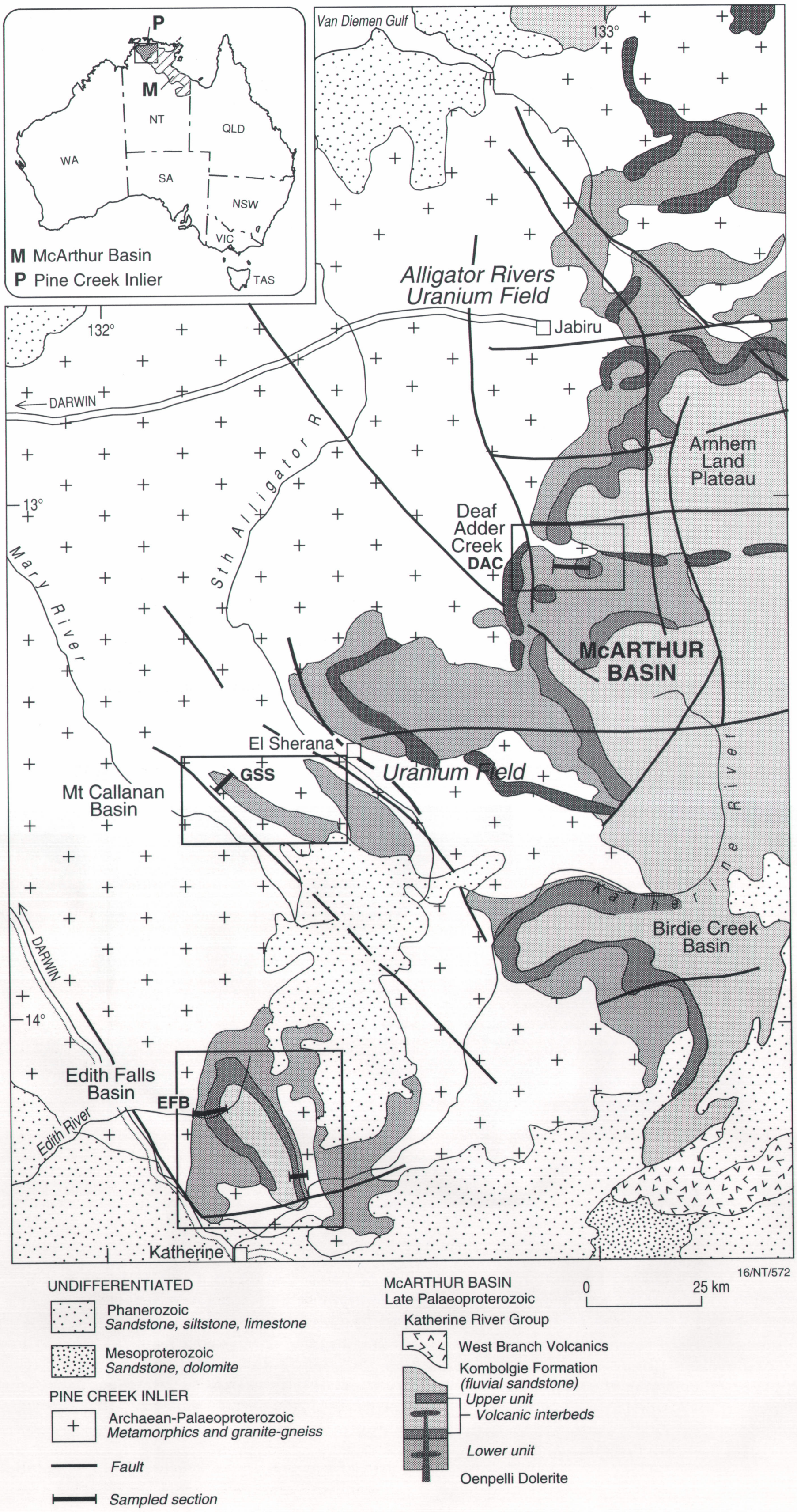

Fig. 14. Generalised geology and location of sampled sections (EFB: 3; GSS: 2; DAC: 2) of the Kombolgie Formation, northwest McArthur Basin.

presence of the remanences, and their intermixing within sections, indicate that the magnetisations are of low-temperature chemical origin. The only plausible source for them is fluid movement through the sediments, at different times, triggered in response to local or regional geological activity.

The remanence of the southeast EFB section is in complete contrast to the other six sections: apart from the presence of the T magnetisation, it is distinguished by two nearly identical, extremely coherent reverse-polarity magnetisations (A_i and A_h), which are almost exclusively magnetite-based. The coherence is more typical of a thermally imposed remanence. Though a small hematite contribution discriminates A_h from A_i, both have a direction similar to A_b and A_f. Since the section is in a gorge adjacent to, and along strike of, a basement-intruding east-northeasterly trending dyke, we regard the magnetisation as a thermally enhanced chemical remanence which records intrusion of a now-eroded dyke into the Kombolgie. Aeromagnetic anomalies over dykes in this area (Tucker et al. 1980: *in* 'Uranium in the Pine Creek Geosyncline', *IAEA, Vienna,* 101–140) support this proposal: their polarity is negative, indicating a contribution from a downward-pointing remanence, precisely what we find in the A_i and A_h magnetisations.

Significance of overprints

The magnetisations identified in the Kombolgie are a palaeomagnetic record of different geological events that have affected it. To interpret their significance we need to know their absolute ages: the fold test results assist here with a partial relative chronology that cannot be violated — from old to young, O > A_b > A_f, A_i, A_h > all remaining groups. We estimate the absolute ages by comparing the overprint pole positions with the calibrated reference APWP for Australia. The best fit with regional geological and palaeomagnetic knowledge is obtained using the 1.8 Ga to Middle Cambrian and late Tertiary segments of the APWP (Fig. 15). The Proterozoic segment includes a major set of primary and overprint results that AGSO obtained from a recently completed extensive palaeomagnetic study of the southeast McArthur Basin for the period ~1.71 to ~1.5 Ga (overviews in Idnurm 1992: *AGSO Research Newsletter*, 17, 2–3; Idnurm et al. 1993: *Exploration Geophysics*, 24, 227–229). Comparison of the Kombolgie overprint poles (labelled KF+group tags) with the reference APWP (Fig. 15) shows that the overprints, from youngest to oldest, record the following events (pole acronyms *italicised* in parentheses):

- *Weathering at ~3 Ma (KFT), possibly the same event that remagnetised the Montejinni Limestone, Wiso Basin (MLO).* The palaeomagnetic age for weathering is consistent with modelled ages of 1–3 Ma for weathering of primary uranium ore at Koongarra (south of Jabiru; Fig. 14) to produce secondary mineralisation. The iron-hydroxide mineralogy detected in the Kombolgie Formation probably derives from this period.
- *Extrusion (KFC) of the extensive Antrim Plateau Volcanics (APV) in the Early Cambrian.* Although best developed at EFB, closest to the northern limit of volcanics outcrop, the record of related fluid activity is still apparent far to the north (DAC).
- *At DAC, fluid activity (KFE) at ~1.4 to ~1.3 Ga (part of the poorly defined segment of the APWP), possibly related to an established phase of dyke intrusion.*

Continued on p. 14

Magnetic secrets of the Palaeoproterozoic Kombolgie Formation revealed

New insights into geological events in the northwest McArthur Basin from palaeomagnetism

Magnetic overprinting of rocks — *secondary* remanence — used to be regarded as a nuisance, interfering with and often thwarting the quest for palaeomagnetism's holy grail: the *primary* palaeopole, the fundamental building-block of a calibrated reference apparent polar-wander path (APWP). In recent years, however, our deepening appreciation of the widespread and common nature of magnetic overprinting, allied with continually improving APWPs for dating overprints, has changed our perception of the phenomenon. No longer of nuisance value, magnetic overprinting now has an important role to play in elucidating the geological history of a region. We can use it to discriminate and date events such as alteration, intrusion, fluid-flow systems, and tectonism that cannot necessarily be resolved by other techniques. We illustrate this role with the highlights of an extensive palaeomagnetic study that AGSO has completed of the Palaeoproterozoic Kombolgie Formation, northwest McArthur Basin (NT).

The unmetamorphosed plateau-forming sandstones and volcanic interbeds of the Kombolgie Formation are the oldest deposits of the northwest McArthur Basin, and crop out over much of western Arnhem Land (Fig. 14). They lie with marked unconformity on basement correlated with the Pine Creek Inlier. The unconformity has economic clout: uranium deposits related to it contain more than 20 per cent of the world's low-cost uranium reserves.

The Kombolgie forms the spectacular scenery of the Arnhem Land Plateau, where it is sub-horizontal, but in small outlier basins along the western margin of the plateau it is gently to steeply dipping. The age of folding is no better constrained than Proterozoic. The unit is dissected by extensive joint and fault systems which add to its scenic value. Aeromagnetic mapping has shown that these systems are the sites of dyke intrusion but, because of differential erosion, dykes rarely crop out, so their age relationships are obscure.

The age of the Kombolgie, the oldest formation of the Katherine River Group, is somewhat older than 1.71 Ga, the SHRIMP (sensitive high-resolution ion-microprobe) zircon age for the West Branch Volcanics (Pietsch et al. 1994: *Proceedings AusIMM Annual Conference*, 135–138), the youngest formation of the Group. The Oenpelli Dolerite intruded the Kombolgie at ~1.69 Ga, and dolerite and phonolite dykes intruding the unit in the northern part of the region shown in Figure 14 have been respectively dated at ~1.37 and ~1.32 Ga (Page et al. 1980: *in* 'Uranium in the Pine Creek Geosyncline', *IAEA, Vienna*, 39–68).

Over 1000 oriented samples for the study were collected at regular stratigraphic intervals of 1–5 m from seven sections at three localities spaced over a distance of 160 km (Fig. 14). The sections are located on both limbs of the Edith Falls Basin (EFB) and Gertrude Springs Syncline (GSS, Mount Callanan Basin), and through the exposed sequence forming the Arnhem Land Plateau near Deaf Adder Creek (DAC). The sections embrace contrasting structural attitudes which allow application of fold tests to elucidate the relative timing of remanence acquisition and folding.

Extensive and detailed thermal demagnetisation of the samples showed that their natural remanence comprised a number of different magnetic directions. After composite and spurious directions were removed, the magnetic directions for six of the sections (excluding the southeast EFB section) cluster into a remarkable eight distinct groups, each characterised by both normal and reverse polarities of magnetisation and typical levels of dispersion. The groups have been tagged the O, A_b, A_f, B, C, D, E, and T magnetisations. The A_b and A_f magnetisations have essentially the same direction, but application of the fold test demonstrates that the O and A_b magnetisations were acquired before folding, that O is older than A_b, and that the remainder were acquired after folding. Clearly, all magnetisations younger than O are overprints. Comparison of the pole corresponding to the O magnetisation with the reference APWP (later), however, shows that this magnetisation too is most likely an overprint. The geographical distribution of the different groups is not uniform: not all magnetisations are found everywhere. Thus, whereas the A_b–A_f and B directions are the most commonly observed and are present at all three localities, the O group occurs only in GSS (Fig. 14); D, only in EFB; and E, only in DAC.

In terms of magnetic mineralogy, the sole carrier of geologically significant remanence in these six sections is hematite (α-Fe_2O_3): there is no evidence for magnetite (Fe_3O_4). For each of the groups, the remanence spans the spectrum of unblocking temperatures for hematite up to the maximum of 680 to 715°C. Maghemite (γ-Fe_2O_3) and the iron hydroxides, goethite (α-FeOOH) and lepidocrocite (γ-FeOOH), were also detected, but are not abundant. The presence of maghemite probably stems from its role as a metastable precursor to hematite in the lepidocrocite → maghemite → hematite transformation. The high unblocking temperatures of the remanences and lack of evidence for even moderate regional heating of the Kombolgie, the geographic variation in the

Continued on p. 15

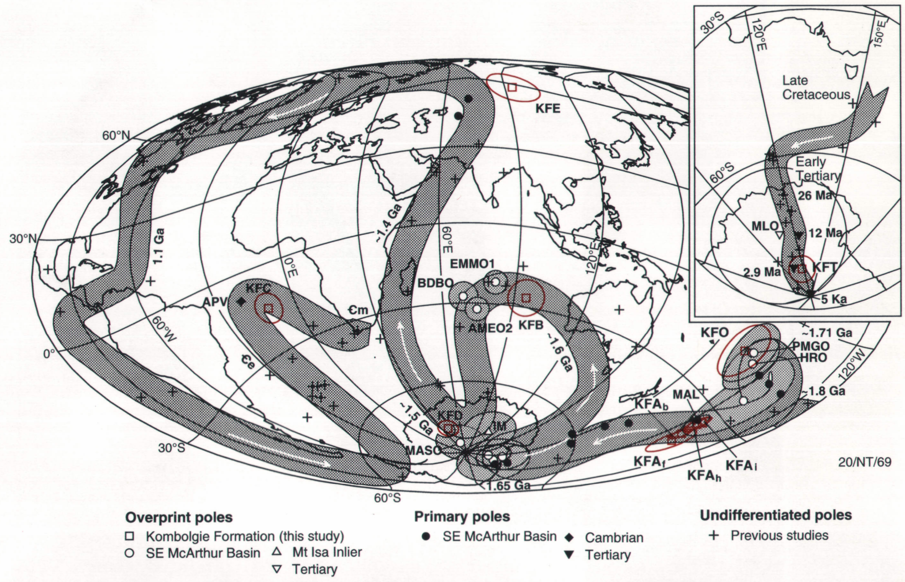

Fig. 15. The Kombolgie Formation overprint poles (in colour, and labelled with 'KF' prefixes to group tags) against the background of the ~1.8 Ga to Middle Cambrian and late Tertiary (inset) segments of the reference APWP for Australia. The Proterozoic segment is based on Idnurm & Giddings (1988: *Precambrian Research*, 40/41, 61–88), updated with results from the southeast McArthur Basin (Idnurm et al. in press: *Precambrian Research*) and Mount Isa (Tanaka & Idnurm in press: *Precambrian Research*). The late Tertiary segment is after Idnurm (1985: *Geophysical Journal of the Royal Astronomical Society*, 83, 399–418). Also shown (light shading) are overprint poles identified in the southeast McArthur Basin and in the Mount Isa Inlier. Circles around overprint poles are the 95% confidence zones. Poles with acronyms are referred to in the text.

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